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LCM2021 – the UK Land Cover Map 2021

Christopher G. Marston, Aneurin W. O'Neil, R. Daniel Morton, Claire M. Wood, and Clare S. Rowland

UK Centre for Ecology and Hydrology, Lancaster Environment Centre, Library Avenue, Bailrigg, Lancaster, LA1 4AP, UK

Correspondence: Christopher G. Marston (cmarston@ceh.ac.uk)

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Abstract. Land cover is a key environmental variable, underpinning widespread environmental research and decision making. The UK Centre for Ecology and Hydrology (UKCEH) has provided reliable land cover information since the early 1990s; this supports multiple scientific, government and commercial objectives. Recent advances in computation and satellite data availability have enabled annual UKCEH land cover maps since 2017. Here, we introduce the latest, annual UK Land Cover Map representing 2021 (LCM2021), and we describe its production and validation. LCM2021 methods replicate those of LCM2017 to LCM2020 with minor deviations in cloud-masking processes and training data sourcing to enhance accuracy. LCM2021 is based on the classification of satellite and spatial context data into 21 land cover or habitat classes, from which a product suite is derived. The production of LCM2021 involved three highly automated key stages: pre-processing of input data, image classification and production of the final data products. Google Earth Engine scripts were used to create an input data stack of satellite and context data. A set of training areas was created based on data harvested from historic UKCEH land cover maps. The training data were used to construct a random forest classifier, which yielded classified images. Compiled results were validated against 35 182 reference samples, with correspondence tables indicating variable class accuracy and an overall accuracy of 82.6 % for the 21-class data and 86.5 % at a 10-aggregated-classes level.

The UK Land Cover Map product suite includes a set of raster products in various projections, thematic and spatial resolutions (10 m, 25 m and 1 km), and land–parcel or vector products. The data are provided in 21-class (all configurations) and aggregated 10-class (1 km raster products only) versions. All raster products are freely available for academic and non-commercial research. The data for Great Britain (GB) are provided in the British National Grid projection (EPSG: 27700) and the Northern Ireland (NI) data are in the TM75 Irish Grid (EPSG: 29903). Information on how to access the data is given in the "Data availability" section of the paper.

1 Introduction

Monitoring and managing environmental change is one of the key challenges for the 21st century (Turner et al., 2007; Allen et al., 2021). Land cover change is both a key cause and a consequence of environmental change (Lambin et al., 2001; Foley et al., 2005), and, as such, it is recognised as a key variable for characterising the environment (Rockström et al., 2009; Bojinski et al., 2014). Land cover affects all aspects of the environment (Foley et al., 2005), including the hydrosphere (Teixeira et al., 2014), atmosphere (Allen et al., 2017) and biosphere (Oliver and Morecroft, 2014), as well as being able to compound or mitigate climate change (Morecroft et al., 2019). Land cover data are therefore an important starting point in many environmental projects and analyses as they form a basis against which other data sets may be integrated and understood (e.g. Coxon et al., 2020). Consequently, there is a demand nationally and internationally for accurate, timely data on land cover. In the United Kingdom (UK), the demand for land cover data has been met by the UK Land Cover Map (LCM) series, comprising LCMs for 1990, 2000, 2007, 2015, 2017, 2018, 2019, 2020 and now 2021. The UK LCMs are a core part of the UK environmental data infrastructure, providing data for a wide range of en-

vironmental applications and for a diverse range of users, including academics, businesses, and government departments and agencies. Government use of land cover data includes informing government decision making by exploring the impact of different land use scenarios (Harrison et al., 2022), creating new data sets to aid the implementation of conservation objectives (Natural England, 2022) and providing for the UK's natural-capital accounts (Office for National Statistics, 2021).

UK LCM data have proven valuable for commercial applications, typically in combination with other data and modelling, in terms of enabling companies to better manage resources and target interventions. For example, water companies have used LCM and modelling to optimise water quality monitoring in areas with high levels of agricultural runoff (United Utilities, 2017). Additionally, telecommunication companies mapped locations of TV "white space" (low or no signal) to target improvements in poor-signal areas using LCM and elevation data (Ishizu and Tran, 2014). LCM data have also enabled companies to make better use of their land, with Highways England using LCM and data modelling to identify and remedy key gaps in biodiversity corridors in their land holdings around roads across SW England (UKCEH, 2021). LCMs have also been used in data services for different sectors of UK industry, including underpinning flood modelling, where LCM data are used in the Flood Estimation Handbook web service, the industry standard for assessing UK flood risk (FEH, 2018). The data have also been used to conserve a protected species by enabling the mapping of Great Crested Newt risk zones (Natural England, 2022), thereby enabling a conservation partnership to sustainably manage the impact of development on newt populations (Tew and Nicolet, 2019), and the data are increasingly used by environmental consultancies for estimating natural-capital accounts (White et al., 2015).

Academic uses of LCM data are wide ranging, including applications in pollution, ecology, hydrology, meteorology and climate change, with research topics motivated by both science and policy-related questions. Ecological applications have included epidemiology (Gulliver et al., 2011); conservation (Hooftman and Bullock, 2012); and modelling spatial distributions for mammals (Croft et al., 2017), insects (Mair et al., 2014), birds (Carrasco et al., 2018), invasive species (Fraser et al., 2015) and pollination (Senapathi et al., 2015; Baude et al., 2016). Hydrological applications have included assessing the impacts of catchment land use on rivers and lakes (Bussi et al., 2016), determining flood risk (Reynard et al., 2001; FEH, 2018), and modelling the impacts of farming on water quality (Taylor et al., 2016). Spatial variability in health has also been explored through the modelling of hay fever risk (McInnes et al., 2017), air pollution impacts on human health (Stedman et al., 1997) and bovine tuberculosis (Wint et al., 2002). In recent years, the LCM has also been used increasingly for mapping ecosystem service provision (Emmett et al., 2016) and natural capital (Norton et al., 2018) and to aid in the creation of new data sets such as the UKCEH Land Cover Plus: Pesticides 2012–2017 maps (Jarvis et al., 2020).

This paper describes the methods and data used to produce the UK Land Cover Map 2021 (LCM2021), as well as the derived LCM2021 data products. LCM2021 was created by classifying satellite data into 21 land cover classes, with these classes being based on the UK Biodiversity Action Plan Broad Habitat definitions (Jackson, 2000). The LCM2021 production process involved three stages: pre-processing of input data, image classification and production of the final data products. We present the results of the classification and the validation of 21-class and 10-class versions of the data set. We describe the different data products available and explain how they can be accessed.

2 Input data sets

Producing a land cover map requires a range of data sets, typically including satellite data and context data, as well as training and validation data. These data sets are described here, followed by the methods in Sect. 3.

2.1 Satellite data

LCM2021 used Sentinel-2 MultiSpectral Instrument (MSI) Level-2A surface reflectance satellite data (Drusch et al., 2012; Claverie et al., 2018) acquired and pre-processed in Google Earth Engine (Gorelick et al., 2017). The images were acquired between 1 December 2020 and 31 January 2022. All 10 and 20 m spectral bands, comprising bands 2 (490 nm), 3 (560 nm), 4 (665 nm), 5 (705 nm), 6 (740 nm), 7 (783 nm), 8 (842 nm), 8a (865 nm), 11 (1610 nm) and 12 (2190 nm), were used.

2.2 Context data

Context data were used as additional inputs to the classification process to enable better classification of the required land cover classes (Rogan et al., 2003). The context data included a digital elevation model (DEM); coastline, foreshore and tidal water layers (to aid coastal classification); building and road layers (to reduce confusion between arable and urban areas) (Table 1); and freshwater and forest layers. The DEM was used to calculate slope and aspect, which were also included as context layers. National cartographic products for Great Britain (GB) were provided by the Ordnance Survey (OS), the national mapping agency of GB, whereas for Northern Ireland (NI), products were provided by a number of government organisations including the NI Statistics and Research Agency (NISRA); the Ordnance Survey Northern Ireland (OSNI); and the NI Department of Agriculture, Environment and Rural Affairs (DAERA). Slightly different context products were available for NI compared to GB (Table 1). The main difference between the OSNI and Ordnance

Survey Great Britain (OSGB) context data is the lack of an NI equivalent to the GB building layer. The OS layers were converted from vector to raster data, with the "distance from" layers created for buildings, roads, rivers and water bodies. The "distance from" products were used to allow the context data products to influence a wider area rather than just the pixels they intersected with. The 10 m NEXTMap digital elevation model (DEM) was used to calculate slope and aspect, with elevation, slope and aspect included as context layers.

2.3 Training-area data

LCM2021 is produced through supervised classification of satellite images, an empirical process that requires training areas of known land cover type. The training areas for the classification were widely distributed to capture the range of spectral signatures typical of each class. For LCM2021, training areas were primarily harvested from existing vector data from LCM2018 (Morton et al., 2020a, b), LCM2019 (Morton et al., 2020c, d) and LCM2020 (Morton et al., 2021e, f). The method is described in Sect. 3.2.1.

2.4 Spatial framework

The LCM spatial framework is a set of land parcel polygons summarising the landscape of the UK into real-world objects such as lakes, fields, woodlands and urban sites. It was derived from generalised digital cartography (Ordnance Survey MasterMap™ topographic layer (OSMM) for GB and Ordnance Survey of Northern Ireland (OSNI) Large-scale Vector for NI), supplemented with rural payment boundary data (Smith et al., 2007; Morton et al., 2011a). The spatial framework was first generated for LCM2007 and revised for LCM2015 onwards by fixing some minor spatial errors and making additional simplifications in terms of land parcel structure. The spatial framework is used to derive a land parcel data set from which 25 m and 1 km raster data sets are generated.

2.5 Validation data sets

Validation data are necessary to establish the accuracy of land cover classifications (Foody, 2002). LCM2021 validation used a UK-wide data set of 35 182 points gathered from field observations, manual interpretation of aerial photography and quality-assured third-party data sets (Fig. 1). The validation data included habitat-mapping and plot data from Countryside Survey data (Wood et al., 2017), supplemented with additional points for arable land (8589 points) collected in 2020 by the Rural Payments Agency. Data from the National Forest Inventory (NFI, 2019) were used to validate the broadleaved woodland and coniferous woodland classes for GB. Further data were gathered from the 2007 LCM validation field survey (Morton et al., 2011a) and were checked against current (circa-2021) aerial photography to ensure

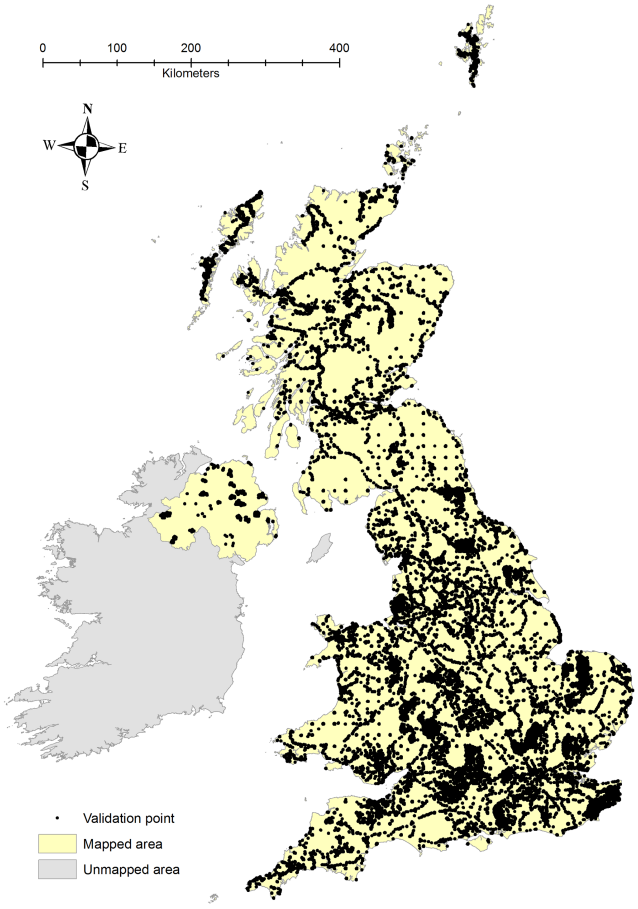

Figure 1. Distribution of the 35 182 validation points for LCM2021.

no change had occurred; some additional manually derived points (interpreted from aerial photography) were also added, particularly for water and urban classes.

3 Methods

Figure 2 shows the key stages in the creation of LCM2021, from image acquisition through to the creation of the final suite of data products.

3.1 Composite-image creation

Temporal composite images (also known as temporal aggregations) are increasingly used to compress voluminous image collections and to overcome problems of data gaps caused by clouds in optical imagery (Carrasco et al., 2019; Holben, 1986). Cloud computation platforms, such as Google Earth Engine (Gorelick et al., 2017), provide users with tools to create composite images aggregated over user-defined intervals (e.g. annually, monthly, bi-monthly) and for

Table 1. Context data set details, including comments on accessibility, data quality and timeliness. [1] Slope and aspect were derived from the DEM data. Abbreviations: Great Britain (GB), Northern Ireland (NI). [2] Data used subject to licensing conditions. [3] Data used under an open license. Ordnance Survey GB open data are from https://osdatahub.os.uk/ (last access: 15 December 2022), Ordnance Survey NI data are from https://www.nidirect.gov.uk/articles/osni-open-data-product-list (last access: 15 December 2022), NI Statistics and Research Agency data are from https://www.opendatani.gov.uk/dataset/settlement-development-limits-2015 (last access: 15 December 2022), DAERA data sets are from https://www.daera-ni.gov.uk/articles/wmu-spatial-datasets (last access: 12 October 2023), and Copernicus Land Monitoring Service data sets are from https://land.copernicus.eu/pan-european/corine-land-cover/clc-2012 (last access: 15 December 2022).

Type of data set	Rationale	Extent	Data provider	Data set name
Topographical	Constrain land cover classes to appropriate slopes and altitudes.	GB	NEXTMap[2]	Digital elevation data[1]
		NI	Ordnance Survey Northern Ireland (OSNI)[3]	10 m digital terrain model height data
Urban extent	Distance from urban and roads, used to limit spectral confusion, especially between arable and urban.	GB	Ordnance Survey (OS)[3] Copernicus Land Monitoring Service[3]	OS VectorMap District, building polygons; OS Open Roads Corine Land Cover 2012, airport polygons
		NI	OSNI[3] NI Statistics and Research Agency[3] Copernicus Land Monitoring Service[3]	Open Data 50k Transport lines; settlement development limits Corine Land Cover 2012, airport polygons
Coastal	Constrain coastal classes so they do not appear inland. Coastal context layer includes foreshore extent, tidal water extent and distance to mean high water line.	GB	OS[3]	OS Terrain 50
		NI	Department of Agriculture, Environment and Rural Affairs (DAERA)[3]	Marine digital data sets
Water	Distance from water used to improve classification of habitats often associated with proximity to rivers (e.g. fen, marsh and swamp, and neutral grassland).	GB	OS[3]	Open Map Local, surface water area polygons
		NI	DAERA[3]	River digital data sets – river segments; lake digital data sets – lake water bodies.
Forest	Improve extent of forest, especially for recently harvested forest and newly planted forest.	GB	OS[3]	OS VectorMap District woodland polygons

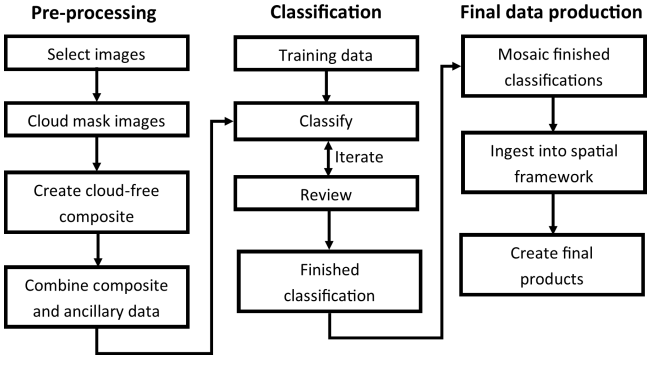

Figure 2. Overview of the processing workflow, showing the three main production phases.

user-defined properties (e.g. raw bands, spectral indices) and with user-defined functions (e.g. median, maximum, mean).

Seasonal composite images of Sentinel-2 Multi-Spectral Instrument (MSI) Level 2-A data (Drusch et al., 2012) were created using Google Earth Engine, with cloud masking based on the Sentinel-2 Cloud Probability layer, s2cloudless (Skakun et al., 2022), and snow masking based on the quality assurance (QA) attributes performed. Images representing median surface reflectance were aggregated over four composite periods: 1 December 2020–31 March 2021, 1 April 2021–30 June 2021, 1 July 2021–31 September 2021 and 1 October 2021–31 January 2022. Periods 1 and 4 were extended by a month into the previous and following years to reduce cloud effects. Seasonal composites were used as they capture the variability in vegetation phenology throughout the year, which aids in the separation of the different land

Table 2. Relationship between the 21 LCM2021 classes, the 10 aggregate classes and the underlying Broad Habitat classes. Italic text highlights classes meeting the Broad Habitat classes as documented in Jackson (2000). [1,2] LCM2021 and aggregate class numbers are used for raster data sets.

LCM2021 aggregate class	LCM2021 aggregate class number[1]	LCM2021 target class	LCM2021 target class number[2]	Associated Broad Habitat
Broadleaf woodland	1	Broadleaved woodland	1	*Broadleaved, mixed and yew woodland*
Coniferous woodland	2	*Coniferous woodland*	2	*Coniferous woodland*
Arable	3	*Arable and horticulture*	3	*Arable and horticulture*
Improved grassland	4	*Improved grassland*	4	*Improved grassland*
Semi-natural grassland	5	*Neutral grassland*	5	*Neutral grassland*
		Calcareous grassland	6	*Calcareous grassland*
		Acid grassland	7	*Acid grassland*
		Fen, marsh and swamp	8	*Fen, marsh and swamp*
Mountain, heath, bog	6	Heather	9	*Dwarf-shrub heath*
		Heather grassland	10	
		Bog	11	*Bog*
		Inland rock	12	*Inland rock*
Saltwater	7	Saltwater	13	Saltwater
Freshwater	8	Freshwater	14	Freshwater
Coastal	9	*Supra-littoral rock*	15	*Supra-littoral rock*
		Supra-littoral sediment	16	*Supra-littoral sediment*
		Littoral rock	17	*Littoral rock*
		Littoral sediment	18	*Littoral sediment*
		Saltmarsh	19	
Built-up areas and gardens	10	Urban	20	*Built-up areas and gardens*
		Suburban	21	

cover classes (Carrasco et al., 2019), and for the UK, aggregation of Sentinel-2 data for four seasons provides data for all four seasons in over 99.9 % of pixels (see SI). Context layers including slope, aspect, elevation distance to coast, distance to building, distance to road and distance to freshwater; in addition, a foreshore mask, a tidal water mask and a forest mask (GB only) were integrated with the composite period satellite imagery (see Table 1 for details of the context data layers, which varied slightly between GB and NI). The addition of context layers reduces spectral confusion between different classes with similar spectral characteristics. The seasonal composites, with the added context data, were then classified.

3.2 Classification

LCM2021 is based on the 21-class nomenclature presented in Table 2. The 21 land cover classes are based on UK Broad Habitat definitions (Jackson, 2000) and are designed to cover the range of habitats found in the UK that can be reliably mapped from satellites. Detailed descriptions of the classes are given in Appendix A. Production of the classifications is split into two stages, first developing the core training areas (Sect. 3.2.1) and then developing the classification process (Sect. 3.2.2).

3.2.1 Core training areas

Selecting appropriate training areas is crucial for the accurate classification of satellite data and has traditionally been time consuming. LCM2021 used a method based on training areas that remained stable across the three previous maps (LCM2018, LCM2019 and LCM2020) on the assumption that many areas such as woodland and urban areas remain stable over decades. Identifying such areas provides a core data set as a starting point for each classification, with this core data set undergoing edits where required to produce the final classification.

When selecting training polygons from this spatial framework and when identifying polygons classified as being the same land cover class for LCM2018, 2019 and 2020, these polygons were also required to have a purity value of $> 80\,\%$ in each of the three land cover classifications to be included. The purity value of a polygon is a measure of the percentage of the modal land cover class over the total number of pixels corresponding to that polygon. The 80 % threshold was selected to retain a high level of purity within the training polygons but also to retain a large enough set of polygons within each classification extent, with the aim of achieving a spatially distributed training data set with a good representation of all land cover classes. Some incorrect training polygons were present within this core training data set due to either misclassifications in the earlier land cover maps or changes in land cover. Systematic visual checks of the train-

ing data and the resultant classifications aided in identifying and removing inappropriate polygons.

3.2.2 Classification algorithm

The composite images were classified using the random forest algorithm (Breiman, 2001) in the WEKA package (Hall et al., 2009; Frank et al., 2016). For each of the tiles, a random forest classifier based on 200 trees was trained. When building a random forest classifier it is important to balance the training samples. An unbalanced classifier will be biased towards common classes, and rare classes may be lost from results completely. Balance was achieved by bagging all training pixels per class then sampling from each bag 10 000 pixels with replacements. For each pixel, the balanced random forest classifier yields a probability of membership for all 21 land cover classes. Land cover per pixel is assigned by highest probability.

3.3 Product construction

Classifications for all tiles were compiled into a full UK spatial coverage at 10 m pixel resolution. This produced a two-band image. Band one is the most likely land cover; band two is the probability associated with this land cover but rescaled into an integer over the interval 0 to 100. Rescaling to an integer enables classification results to be stored in 8-bit, thereby reducing data size without degrading information. The 10 m raster is the precursor for all derived products.

The ingestion into the spatial framework involved determining the majority (modal) class for each polygon. Separate GB and NI data sets were created to accommodate the different map projections. Figure 3 shows the extents of the 32 composites used to achieve complete coverage of the UK. The approximate 100×100 km tile size, based on a modified version of the Ordnance Survey 100 km tile grid, was chosen as this provides a manageable size for processing. Some tiles such as those encompassing the Western Isles, Orkney and Shetland, and Cornwall and the Scilly Isles are intentionally enlarged to avoid a sparsity of training data due to the extensive presence of sea in these tiles. Occasionally, where tile extents are modified, overlap between adjacent tiles does occur.

Once the GB and NI classification mosaics were complete, a series of minor knowledge-based corrections was applied. These included the reclassification of misclassified arable pixels to improved grassland in urban green-space areas (as denoted by the OS Open Greenspace data set) and of coastal classes misclassified inland using a coastal mask.

3.4 Validation

The LCM2021 class was extracted for each of the validation points. From these data, confusion matrices were plotted for the 21 target classes and the 10 aggregate classes used for LCM2021.

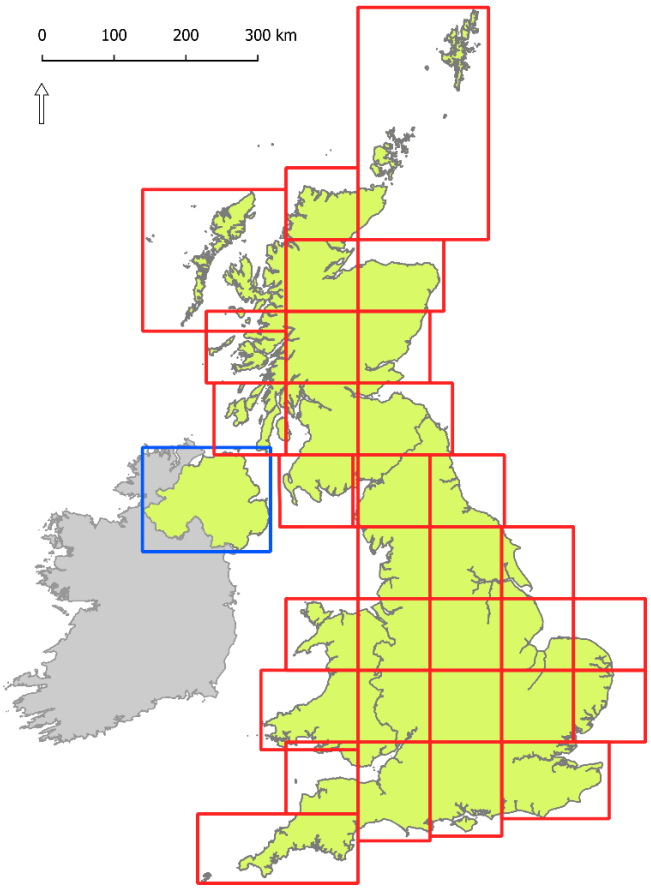

Figure 3. Composite-image extents comprising LCM2021 for Great Britain (red) and Northern Ireland (blue).

4 Results

4.1 Validation results

The 25 m rasterised polygon version of LCM2021 (Marston et al., 2022e, f) was validated using 35 182 points distributed across the UK (Table 3). The results are summarised in a confusion matrix, which shows how reference points for each of the classes were classified. Ideally, all the points would fall along the main diagonal, showing complete agreement between the reference data and the classification. Table 3 shows that LCM2021 has an overall accuracy of 82.6 %, with the accuracy of individual classes varying. The results of the validation are shown in a confusion matrix (Table 3), with the reference data in the columns and the classification data in the rows. The confusion matrix shows the level of agreement between the classification and the reference data, as well as the areas of disagreement or confusion. The accuracy varies with class, with the producer's accuracy ranging between high and low values of 93.9 % (saltmarsh) and

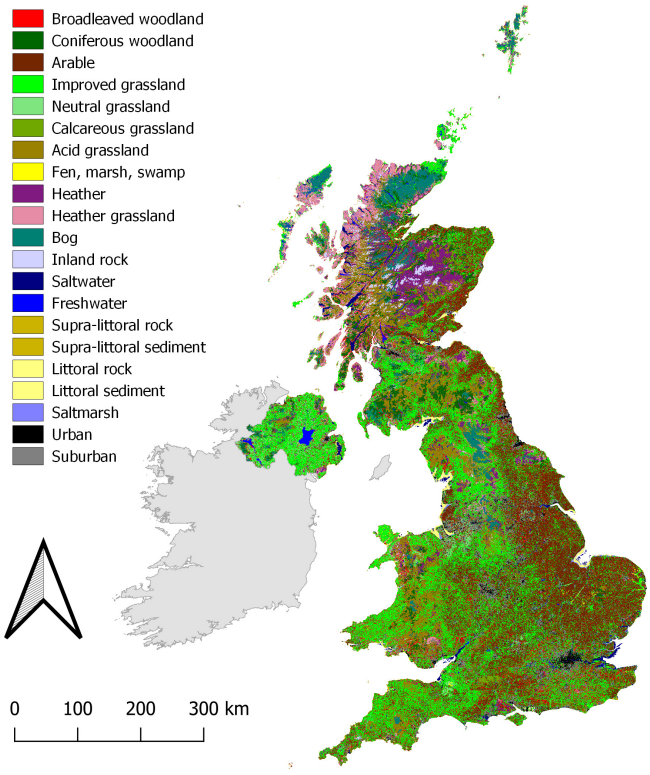

Figure 4. LCM2021 in standard colour palette (see Table B2 for palette details) (see Appendix B for LCM2021 in revised colour palette).

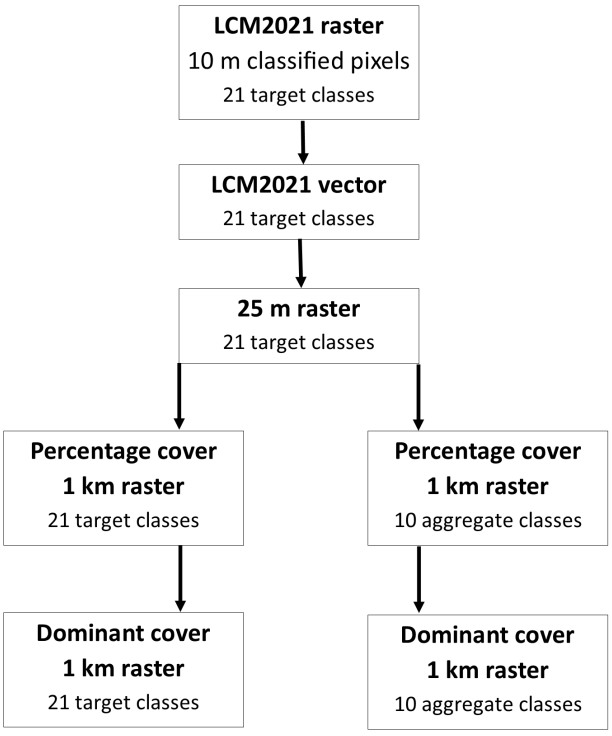

Figure 5. Overview of the LCM2021 data set production process. The vector version of the data set is constrained by licensing restrictions due to the inclusion of national mapping agency data.

35.4 % (heather grassland) and the user's accuracy varying between 96.1 % (arable) and 42.6 % (heather grassland). For the products that use the 10 aggregate classes (see Sect. 5 for more details about the aggregate-class products), the validation suggests an overall accuracy of 86.5 % (Table 4).

4.2 LCM2021 map

The final LCM2021 product shows the expected distribution of classes across the UK (Fig. 4). At the scale shown in Fig. 4, the differences between the grassland of the west and the arable areas in the east are clear, as are the uplands in Wales and Scotland, with London, the UK's largest urban area, clearly visible.

4.3 LCM statistics

One of the uses of LCM2021 is to produce country-level statistics (Table 5), although land cover statistics can also be produced for other types of spatial units, such as river or lake catchments or national parks and protected areas.

5 LCM2021 data products

LCM2021 is provided in a range of open data formats and in a range of thematic and spatial resolutions to support the needs of a wide range of users and applications. There are 21 target classes in the full-thematic-resolution product and 10 classes in the aggregated products (Table 2). The base product is the 10 m raster (Marston et al., 2022a, b) from which all other products are derived (Fig. 5). The LCM2021 10 m raster is ingested into the spatial framework to produce a vector version of the data set (Marston et al., 2022c, d). The vector version of the data set is then used to create a rasterised polygon version of the data set with a 25 m pixel size (Marston et al., 2022e, f). The 25 m version is effectively the legacy-style land cover map and maintains a spatial consistency with the earlier Landsat-based land cover maps of LCM1990 (Rowland et al., 2020a, b), LCM2007 (Morton et al., 2011b, 2014) and LCM2015 (Rowland et al., 2017a, b); LCM2000 (Fuller et al., 2002a, b) currently uses a different spatial structure. The 25 m raster product is then used to produce the 1 km percentage cover and dominant cover products for both the 21 target classes and the 10 aggregate classes (Marston et al., 2022g). The Great Britain and Northern Ireland data sets are provided separately, with the GB data in the British National Grid projection (EPSG:27700)

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Table 3. Confusion matrix for LCM2021 against 35 182 reference points. BW refers to broadleaved woodland; CW refers to coniferous woodland; AR refers to arable; IG refers to improved grassland; NG refers to neutral grassland; CG refers to calcareous grassland; AG refers to acid grassland; FMS refers to fen, marsh and swamp; H refers to heather; HG refers to heather grassland; B refers to bog; IR refers to inland rock; SW refers to saltwater; FW refers to freshwater; SLR refers to supra-littoral rock; SLS refers to supra-littoral sediment; LR refers to littoral rock; LS refers to littoral sediment; SM refers to saltmarsh; U refers to urban; SU refers to suburban; PA refers to producer's accuracy; U refers to user's accuracy; OA refers to overall accuracy.

Classified data	Reference data																						
	BW	CW	AR	IG	NG	CG	AG	FMS	H	HG	B	IR	SW	FW	SLR	SLS	LR	LS	SM	U	SU	Total	UA (%)
BW	1704	218	19	73	24	0	10	0	5	26	2	4	0	9	1	0	0	1	1	2	13	2112	80.7
CW	55	649	3	1	1	1	4	0	5	16	3	0	0	0	0	0	0	0	0	1	0	739	87.8
AR	22	3	10 102	306	28	1	2	0	0	3	1	10	0	6	0	0	0	0	1	13	13	10 511	96.1
IG	100	4	1027	4835	186	55	175	18	1	82	29	4	0	8	0	26	1	0	4	9	24	6588	73.4
NG	18	11	39	230	503	0	13	19	2	4	0	0	0	3	0	0	0	1	0	2	0	845	59.5
CG	30	4	26	47	4	946	15	0	1	6	0	13	0	0	0	0	0	0	0	1	0	1093	86.6
AG	20	1	88	177	6	55	1245	0	29	228	39	1	0	1	0	0	0	0	0	0	4	1894	65.7
FMS	15	0	5	14	2	1	4	577	0	0	2	0	0	8	0	0	0	0	0	0	0	628	91.9
H	7	1	9	1	0	0	30	1	819	104	121	0	0	0	1	0	0	0	0	0	0	1094	74.9
HG	17	3	9	12	0	5	158	3	81	299	106	4	0	3	0	1	0	0	0	0	1	702	42.6
B	0	3	0	3	0	3	31	4	27	71	877	0	0	1	0	0	0	0	0	0	0	1020	86.0
IR	0	0	10	2	1	9	4	0	3	2	2	125	0	0	0	0	0	0	0	8	0	166	75.3
SW	0	0	0	0	0	0	0	0	0	0	0	0	73	0	0	0	0	13	0	0	0	86	84.9
FW	13	0	1	4	1	0	1	2	0	0	0	0	0	548	0	0	0	0	0	0	2	572	95.8
SLR	0	0	0	5	0	0	7	0	0	0	0	0	0	0	42	6	11	6	0	0	0	77	54.5
SLS	1	0	3	2	4	0	1	0	0	0	0	0	0	0	1	178	0	7	1	0	0	198	89.9
LR	0	0	0	0	0	0	0	0	0	1	0	1	0	0	16	5	86	17	0	1	0	127	67.7
LS	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	11	7	211	3	0	0	241	87.6
SM	2	0	0	5	1	0	0	13	0	1	0	0	0	2	1	8	1	9	169	0	0	212	79.7
U	19	0	12	29	15	0	1	1	0	0	0	26	0	3	0	7	1	2	1	2343	303	2763	84.8
SU	151	1	17	223	44	0	2	0	1	1	2	10	0	3	0	3	0	0	0	329	2727	3514	77.6
Total	2174	898	11 370	5969	820	1076	1703	638	974	844	1184	198	82	595	62	245	107	267	180	2709	3087	35 182	
PA (%)	78.4	72.3	88.8	81.0	61.3	87.9	73.1	90.4	84.1	35.4	74.1	63.1	89.0	92.1	67.7	72.7	80.4	79.0	93.9	86.5	88.3		
OA (%)											82.6												
Kappa											0.794												

Table 4. Confusion matrix for LCM2021 aggregate classes against 35 182 reference points. BW refers to broadleaved woodland; CW refers to coniferous woodland; AR refers to arable; IG refers to improved grassland; SNG refers to semi-natural grassland; MHB refers to mountain, heath and bog; SW refers to saltwater; FW refers to freshwater; C refers to coastal; BU refers to built-up and gardens; PA refers to producer's accuracy; UA refers to user's accuracy; OA refers to overall accuracy.

Classified data	Reference data											
	BW	CW	AR	IG	SNG	MHB	SW	FW	C	BU	Total	UA (%)
BW	1704	218	19	73	34	37	0	9	3	15	2112	80.7
CW	55	649	3	1	6	24	0	0	0	1	739	87.8
AR	22	3	10 102	306	31	14	0	6	1	26	10 511	96.1
IG	100	4	1027	4835	434	116	0	8	31	33	6588	73.4
SNG	83	16	158	468	3390	325	0	12	1	7	4460	76.0
MHB	24	7	28	18	249	2641	0	4	2	9	2982	88.6
SW	0	0	0	0	0	0	73	0	13	0	86	84.9
FW	13	0	1	4	4	0	0	548	0	2	572	95.8
C	3	0	3	12	26	3	9	2	796	1	855	93.1
BU	170	1	29	252	63	40	0	6	14	5702	6277	90.8
Total	2174	898	11 370	5969	4237	3200	82	595	861	5796	35 182	
PA (%)	78.4	72.3	88.8	81.0	80.0	82.5	89.0	92.1	92.5	98.4		
OA (%)						86.5						
Kappa						0.834						

Table 5. UK land cover statistics derived from LCM2021 in area (km^2) calculated from the 10 m raster product.

Land cover code	Land cover class	UK	England	Scotland	Wales	Northern Ireland
1	Broadleaved woodland	21 045	12 322	5330	2555	838
2	Coniferous woodland	13 830	2788	9022	1422	598
3	Arable	49 121	41 867	5960	841	453
4	Improved grassland	66 394	39 304	13 053	7765	6272
5	Neutral grassland	4200	1659	105	525	1911
6	Calcareous grassland	2561	2387	31	11	132
7	Acid grassland	21 873	4448	12 281	4404	740
8	Fen	783	471	68	182	62
9	Heather	11 562	2081	8636	566	279
10	Heather grassland	11 842	1433	9719	409	281
11	Bog	10 457	1986	7255	251	965
12	Inland rock	2685	245	2362	63	15
13	Saltwater	935	720	53	4	158
14	Freshwater	3267	1093	1499	96	579
15	Supra-littoral rock	390	62	252	66	10
16	Supra-littoral sediment	723	169	340	102	112
17	Littoral rock	432	84	340	1	7
18	Littoral sediment	1444	1248	78	34	84
19	Saltmarsh	923	552	272	95	4
20	Urban	4901	4066	482	227	126
21	Suburban	17 539	13 669	1812	1308	750
	Total area (km^2)	246 902	132 651	78 949	20 927	14 375

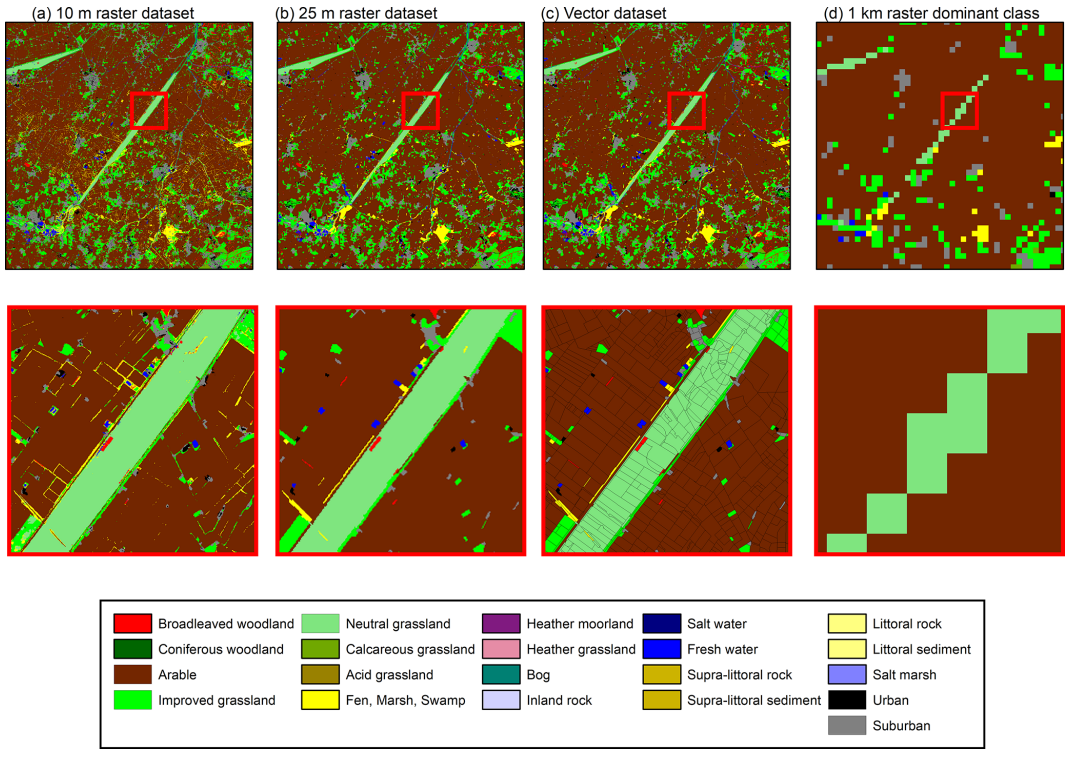

Figure 6. Examples of the level of spatial detail provided by the **(a)** 10 m raster, **(b)** 25 m rasterised polygons, **(c)** vector data set and **(d)** 1 km raster data sets. The top panel shows the zoomed-out view, and the red box shows the location of the zoomed-in area in the lower panels.

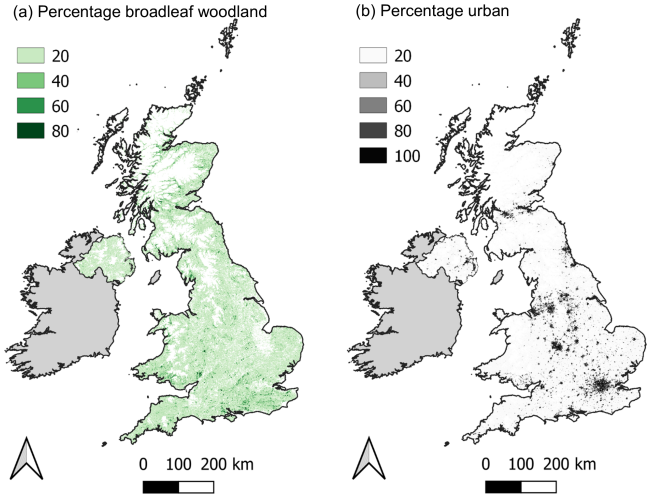

Figure 7. Examples of the UK-wide distribution of **(a)** broadleaf woodland and **(b)** built-up areas and gardens in terms of percentage cover based on the 1 km aggregate class percentage data sets for GB and NI (Marston et al., 2022g).

and the Northern Ireland data in the Irish Grid projection (EPSG:29903).

LCM2021 is produced with a range of spatial resolutions (Fig. 6) to support different types of analyses. The 10 m data set is a relatively new data set (first produced in LCM2020) and is enabled by the 10 m resolution of the optical Sentinel-2 bands. The higher-spatial-resolution products capture the fine detail of the landscape and are often used for the assessment of landscape features requiring a fine resolution, such as habitat connectivity (Hooftman and Bullock, 2012), or for detailed studies of small areas (e.g. Miller et al., 2020). The 1 km data sets are primarily used for national-scale modelling, often in conjunction with a range of other coarser-resolution environmental data sets (e.g. Coxon et al., 2020; Jordan et al., 2022), and these are useful for showing the distribution of a particular class across the UK. For example, Fig. 7 shows the distribution of the broadleaf woodland class and the urban class from the aggregated 1 km percentage data sets for the UK.

6 Data availability

The LCM2021 data products (Table 6) have digital object identifiers (DOIs) and are available via the NERC Environmental Data Service (https://eds.ukri.org/environmental-data-service, last access: 15 December 2022), with all versions listed on the LCM2021 data collection page (https://catalogue.ceh.ac.uk/documents/017313c6-954b-4343-8784-3d61aa6e44da, UKCEH, 2022a). Raster data are provided as uncompressed GeoTIFFs and are supplied with data set documentation and

Table 6. Digital object identifier (DOI) for the LCM2021 openly available products.

Product	Region	DOI	Reference
10 m classified pixels	GB	https://doi.org/10.5285/a22baa7c-5809-4a02-87e0-3cf87d4e223a	Marston et al. (2022a)
	NI	https://doi.org/10.5285/e44ae9bd-fa32-4aab-9524-fbb11d34a20a	Marston et al. (2022b)
25 m rasterised land parcels	GB	https://doi.org/10.5285/a1f85307-cad7-4e32-a445-84410efdfa70	Marston et al. (2022e)
	NI	https://doi.org/10.5285/f3310fe1-a6ea-4cdd-b9f6-f7fc66e4652e	Marston et al. (2022f)
1 km summary raster data	GB and NI	https://doi.org/10.5285/a3ff9411-3a7a-47e1-9b3e-79f21648237d	Marston et al. (2022g)

QGIS files for displaying the classifications in the LCM standard palette (used since LCM2000) (see Table B1 in Appendix B, for example) and a palette designed to aid users affected by colour-vision deficiency (see Fig. B1, for example). The 10 m raster data sets are also viewable via a web mapping service (https://catalogue.ceh.ac.uk/documents/2ad19a50-b940-469e-a40d-17818b77020c, UKCEH, 2022b).

All LCM raster data sets are available under a single common licence without charge for non-commercial use, which includes non-commercial research and use within public bodies and charities and their contractors. Alternative licensing can be arranged on request with commercial organisations who wish to use the data sets within their own internal business operations or to develop commercial products or services.

7 Conclusions

The UK Land Cover Map series, comprising LCM1990 (formerly LCMGB) (Fuller et al., 1994), LCM2000 (Fuller et al., 2002c), LCM2007 (Morton et al., 2011b), LCM2017, LCM2018, LCM2019 and LCM2020, underpins a wide range of UK environmental science analyses, and LCM2021 is expected to continue this trend. The accuracy of LCM2021 varies with class, but it has an overall accuracy of 82.6 % for the 21 target classes and of 86.5 % for the 10 aggregate classes.

Appendix A: Notes on LCM2021 land cover classes

Table A1. Discussion and commentary on each of the UK LCM2021 land cover and habitat classes. See Jackson (2000) for a description of the underlying Broad Habitat classes.

LCM2021 land cover class	Notes
Broadleaved woodland	In the UK BAP (Biodiversity Action Plan) broadleaved-, mixed- and yew-woodland Broad Habitat definition (Jackson, 2000), the broadleaved woodlands are characterised by stands > 5 m high with tree cover of > 20 %. Scrub (< 5 m) requires a cover of > 30 % for inclusion. Such fine distinctions cannot be made through optical remote sensing. Open-canopy woodland (stands with trees < 50 %) is a particular problem, albeit one that occurs relatively rarely in the UK; such areas are likely to be confused with other classes due to the dominance of the non-woodland vegetation and the sparsity of training areas representing these areas. In the UK, broadleaved evergreen trees rarely occur in stands of > 0.5 hectares, an area large enough to create training areas suitable for classification. Consequently the classifier is likely to struggle with this land cover. These stands may be classified as coniferous woodland because of the full-year chlorophyll signal. Mixed-woodland stands of broad-leaved or evergreen trees exceeded the minimum mappable unit, and they were treated as separate blocks within the woodland; in many parts of the UK, truly mixed woodlands as opposed to those with mosaic blocks of broadleaved and coniferous trees are unusual. Stands with near-closed canopies can be interpreted easily in the field, and pure examples can normally be found for training the classifier.
Coniferous woodland	The UK BAP coniferous-woodland class includes semi-natural stands and plantations, with cover of > 20 %. Classification of coniferous woodland is generally straightforward, but rare examples of open-canopy semi-natural pinewoods are likely to be classified according to the dominant understorey class. The UK BAP includes new plantations and recently felled areas. These are for land use and not land cover. Newly felled areas are often dominated by grass, heather and encroaching vegetation and are more likely to be classified as these instead of coniferous woodland. Deciduous larch has potential to be confused with broadleaved deciduous woodland but is generally correctly identified.
Arable and horticulture	The BAP Broad Habitat of arable and horticulture includes annual crops, perennial crops such as berries and orchards, and freshly ploughed land. This is a very broad class, and as a consequence, it has large potential for spectral confusion with non-arable surfaces. The main confusion between arable and other classes occurs between arable land and improved grassland. This is especially likely when grassland is managed by cutting, followed by periods of low growth and reflectance from chlorophyll. When this happens, the observed seasonal reflectance pattern can be similar to Graminid crops, such as wheat and barley. Indeed, grass managed in this way is technically a crop so an arable classification is not necessarily wrong.
Improved grassland	Improved grassland is distinguished from semi-natural grasslands based on its higher productivity, lack of winter senescence, location and/or context. Grasslands lie on a continuum so some confusion with other grassland types is inevitable. Confusion with grass-like crops will also occur.
Neutral grassland	The UK BAP Broad Habitat of neutral grassland is expected to be challenging for satellite-based classification. The BAP class of neutral grassland is defined by botanical composition and includes semi-improved grasslands managed for silage, hay or pasture (Jackson, 2000). There is not generally an obvious spectral difference between these and other productive grass types. However, the inclusion of context rasters for slope and distance to rivers appear to have helped greatly with neutral-grassland detection.
Calcareous grassland	The calcareous-grassland class is mapped spectrally. However, the inclusion of context layers for slope is expected to improve results. UKCEH does not have free access to a highly resolved soil PH or soil type layer, which we would expect to help further. For regions known to contain substantial coverage of calcareous grassland, for example the limestone dales of Derbyshire and North Yorkshire, the South Downs, and Salisbury Plain, our results match expectations.
Acid grassland	The UK BAP acid-grassland class can be spectrally variable, depending on the dominant species composition. Deciduous acid grassland, dominated by *Molinea caerula*, has a distinct signal compared to acid grasslands dominated by mixtures of other grasses, rushes, mosses, herbs and sedges. In other work, we have been able to refine this class successfully. However, we did not make this separation in historical maps so we are not able to retrieve suitable observations from bootstrap training. Bracken has a very distinctive spectral signal but only at certain times of the year when its foliage begins to dominate its grassland understorey. Historically, with restricted availability of satellite images, we could not reliably separate the UK BAP bracken class from acid grassland so we combined these into a single land cover class. With the greater image frequency and therefore better access to seasonal signals, it may now be possible to overcome this historic limitation, but to do this, we will need novel training data as we will not be able to retrieve a signal from bootstrap training.
Heather and heather grassland	For LCM2007 we refined the BAP dwarf-shrub and heath class into two classes, depending on the density of heather, producing the heather and heather grassland classes (it is heather when there is more than 25 % heather cover). This was to retain some consistency between the LCM1990 and LCM2000 classes of open-shrub heath and dense-shrub heath. In some parts of the UK, significant areas of low-lying non-heather shrubs occur. For example, gorse can form a dominant shrub layer. Note that the land cover maps typically show confusion over heather, heather grassland and bog. However, they are often difficult to separate in the field. It is challenging to accurately estimate coverage above and below the defining threshold.

Table A1. Continued.

LCM2021 land cover class	Notes
Fen, marsh and swamp	The UK BAP fen, marsh and swamp class includes fen, fen meadows, rush pasture, swamp, flushes and springs. From a remote sensing perspective, the fen, marsh and swamp class is problematic as it can be comprised of a wide range of vegetation types, and many patches are below the minimum mapping unit (MMU) of the UKCEH land parcel spatial framework. The small size of many fen, marsh and swamp patches and their typically mosaic nature make it difficult to find reliable training data. Consequently, the fen, marsh and swamp class is likely to be underestimated in some regions. However, substantial areas of contiguous reed dominated fenland appear to be well detected.
Bog	The UK BAP class of bog includes ericaceous, herbaceous and mossy swards in areas with a peat depth of > 0.5 m. We cannot detect peat depth from satellites. Vegetation in deep-peat soils represents a continuum involving acid grassland, dwarf-shrub heath and some types of fen, marsh and swamp, and the separation of continuously varying land cover into discrete types can be difficult, especially when they exist in a complex small-patch mosaic and when their definitions are vague. We retain the bog class to maintain consistency with historical LCM products, and the random forest classifier learns bog presence based on training data automatically generated from these. The predicted distribution occurs in regions where it is expected and so is a good indicator of where bog is likely to occur. However, bog and the range of upland vegetation classes are expected to occur in peaty soils (acid grassland, fen marsh and swamp; heather; and heather grassland), potentially causing interclass confusion. This is partly due fine-scale variation but is largely an effect of ambiguous definitions. The UK BAP Broad Habitats (on which UKCEH land cover classes are based) were not defined with satellite remote sensing in mind.
Saltwater	Saltwater is rarely different spectrally from freshwater, and the saltwater distribution predicted by the random forest classifier is determined by coastal-context rasters in classification scenes. There will be some confusion between saltwater and freshwater in tidal rivers, but this will not be substantial. Occasionally, saltwater is confused with non-vegetated surfaces close to the coast, and this happens because the automatically generated saltwater training classes coincide with the tide being out in the satellite view. The effect has so far been trivial, but the result is that we predict saltwater with slightly lower accuracy than freshwater. Our main goal is to map land cover so coastal water and intertidal regions are not a high priority.
Freshwater	The UKCEH freshwater class comes from merging two BAP BHs (standing open water and canals, rivers and streams) since they cannot be separated by spectra. In many cases, small and/or narrow water bodies fall below the MMU of the UKCEH land parcel spatial framework and so effectively disappear into the dominant surrounding vegetation. Where these features are appropriately aligned and sufficiently wide, they may be detected and, if so, will be available in the raster classification data sets. Water bodies > 0.5 ha and wider than 40 m are mapped with very high accuracy. The exceptions are temporary water bodies and quarries. Water in some quarries is strongly affected by the minerals in the rock and can result in atypical colours and misclassification.
Inland rock	The BAP Broad Habitat of inland rock covers both natural and artificial exposed rock surfaces which are > 0.25 ha, such as inland cliffs, caves, screes and limestone pavements, as well as various forms of excavations and waste tips such as quarries and quarry waste. Opportunistic vegetation is common amongst rocky landscapes. We classify UKCEH inland rock if rock has the dominant signature.
Urban and suburban	Within the built-up areas and gardens BAP Broad Habitat, we can reliably separate two UKCEH categories: urban and suburban. Urban includes dense urban, such as town and city centres, where there is little, if any, vegetation. Urban also includes areas such as dock sides, car parks and industrial estates. It is sometimes confused with other non-vegetated surfaces – for example, open-cast quarries or, more rarely, coastal rocks or ploughed fields. Suburban includes suburban areas where the spectral signature is a mix of urban and vegetation signatures. Suburban and urban lie on a continuum, and confusion is expected.
Supra-littoral rock	Features that may be present in this coastal class include vertical rock, boulders, gullies, ledges and pools generally forming a narrow band when viewed from above. Only limited areas can be mapped using satellite remote sensing.
Supra-littoral sediment	This class includes sand dunes, which are reliably mapped. There may be confusion in terms of areas of coastal sand between this class and the littoral sediment class. Supra-littoral sediments can stabilise and from increasing volumes of vegetation. Heavily vegetated littoral sediment is likely to be classified as a vegetation class.
Littoral rock	These classes are those in the maritime zone on a rocky coastline. They are generally more extensive than supra-littoral rock and are thus more readily detected using satellite images.
Littoral sediment; and saltmarsh	The BAP Broad Habitat of littoral sediment has a subclass, the BAP Priority Habitat of saltmarsh. Saltmarsh is generally distinct from nearby vegetation and only occurs near the coast. As a consequence we can map this well with remote sensing. The saltmarsh class is occasionally subject to commission error, where we mistake other vegetation in the coastal zone (mainly arable) as saltmarsh. The littoral sediment is sometimes confused with the supra-littoral sediment class.

Appendix B: Display of LCM products

The UK Land Cover Map can be displayed however users require. However, standard and revised colour palettes are available (Tables B1 and B2) and are supplied as QGIS symbology files to enable users to rapidly display products.

Table B1. Standard LCM colour palette.

Land cover	Land cover class number	Red	Green	Blue
Broadleaved woodland	1	255	0	0
Coniferous woodland	2	0	102	0
Arable and horticulture	3	115	38	0
Improved grassland	4	0	255	0
Neutral grassland	5	127	229	127
Calcareous grassland	6	112	168	0
Acid grassland	7	153	129	0
Fen, marsh and swamp	8	255	255	0
Heather	9	128	26	128
Heather grassland	10	230	140	166
Bog	11	0	128	115
Inland rock	12	210	210	255
Saltwater	13	0	0	128
Freshwater	14	0	0	255
Supra-littoral rock	15	204	179	0
Supra-littoral sediment	16	204	179	0
Littoral rock	17	255	255	128
Littoral sediment	18	255	255	128
Saltmarsh	19	128	128	255
Urban	20	0	0	0
Suburban	21	128	128	128

Table B2. Revised colour palette avoiding use of red.

Land cover class	Land cover class number	Red	Green	Blue
Broadleaved woodland	1	51	160	44
Coniferous woodland	2	0	80	0
Arable and horticulture	3	240	228	66
Improved grassland	4	1	255	124
Neutral grassland	5	220	153	9
Calcareous grassland	6	255	192	55
Acid grassland	7	178	145	0
Fen, marsh and swamp	8	253	123	238
Heather	9	128	26	128
Heather grassland	10	230	140	166
Bog	11	205	59	181
Inland rock	12	210	210	255
Saltwater	13	0	0	92
Freshwater	14	0	0	255
Supralittoral rock	15	152	125	183
Supralittoral sediment	16	204	179	0
Littoral rock	17	255	255	128
Littoral sediment	18	255	255	128
Saltmarsh	19	128	128	255
Urban	20	0	0	0
Suburban	21	128	128	128

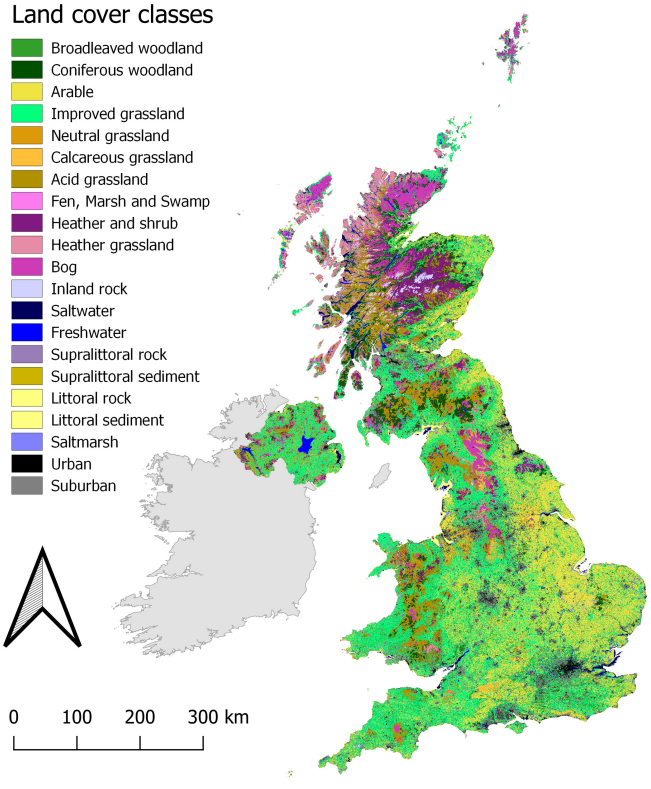

Figure B1. Land Cover Map 2021 in revised colour palette (details of revised colour palette in Table B2).

Author contributions. RDM and CSR acquired funding. CGM, CSR and RDM pre-processed the data and conducted classifications. RDM designed and implemented the random forest classification software and supporting computation structures with input from the whole team. CSR, RDM and CGM developed the code for pre-processing the satellite data. CGM, CSR and AWO reviewed the classifications. CSR, CGM and AWO prepared the validation data. CSR and CGM prepared the paper with contributions from RDM, AWO and CMW. RDM, CSR and CGM designed the project. CGM led the production of LCM2021.

Competing interests. The contact author has declared that none of the authors has any competing interests.

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Cartographic and DEM data for NI are from the settlement development limits of the © Northern Ireland Statistics and Research Agency (NISRA) (2015). NI open data layers for coastal water and freshwater are from the © Department of Agriculture, Environment and Rural Affairs, Northern Ireland. OSNI digital elevation data and road network data contain public-sector information licensed under the terms of the Open Government Licence v3.0. Urban green-space correction used green-space areas for NI, identified from OpenStreetMap data provided by OpenStreetMap and available under the Open Database License.

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