LCM2021 – The UK Land Cover Map 2021

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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) have provided reliable land cover information since the early 1990's; 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 describe its production and validation. LCM2021 methods replicate those for 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/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-class 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/vector product. The data are provided in 21-class (all configurations) and aggregated 10-class versions (1 km raster products only). 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 (https://epsg.io/27700) and the Northern Ireland (NI) data are in the TM75 Irish National Grid (https://epsg.io/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 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 & Morecroft, 2014), as well as being able to

32 compound or mitigate climate change (Morecroft et al., 2019). Land cover data are therefore an important starting point in
33 many environmental projects and analyses, as they form a basis against which other data sets may be integrated and
34 understood (e.g. Coxon et al., (2020)). Consequently, there is a demand nationally and internationally for accurate, timely
35 data on land cover. In the United Kingdom (UK), the demand for land cover data has been met by the UK Land Cover Map
36 (LCM) series, comprising LCMs for 1990, 2000, 2007, 2015, 2017, 2018, 2019, 2020 and now 2021. The UK LCMs are a
37 core part of the UK environmental data infrastructure providing data for a wide range of environmental applications and for
38 a diverse range of users, including academics, businesses, and government departments and agencies. Government use of
39 land cover data includes informing government decision-making by exploring the impact of different land-use scenarios
40 (Harrison et al., 2022), creating new data sets to aid implementation of conservation objectives (Natural England, 2022),
41 and providing for the UK's Natural Capital accounts (Office for National Statistics, 2021).

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43 UK LCM data have proven valuable for commercial applications, typically in combination with other data and modelling,
44 to enable companies to better manage resources and target interventions. For example, water companies have used LCM
45 and modelling to optimise water quality monitoring in areas with high levels of agricultural run-off (United Utilities, 2017).
46 Additionally, telecommunications companies mapped locations of TV 'white space' (low/no signal) to target improvements
47 in poor signal areas using LCM and elevation data (Ishizu & Tran, 2014). LCM data has also enabled companies to make
48 better use of their land, with Highways England using LCM and data modelling to identify and remedy key gaps in
49 biodiversity corridors in their land holdings around roads across SW England (UKCEH, 2021). LCM has also been used in
50 data services for different sectors of UK industry, including underpinning flood modelling, where LCM data are used in the
51 Flood Estimation Handbook web service, the industry standard for assessing UK flood risk (FEH, 2018). The data have also
52 been used to conserve a protected species, by enabling the mapping of Great Crested Newt risk zones (Natural England,
53 2022) enabling a conservation partnership to sustainably manage the impact of development on newt populations (Tew &
54 Nicolet, 2019), and are increasingly used by environmental consultancies for estimating Natural Capital accounts (White et
55 al., 2015).

56

57 Academic uses of LCM data are wide-ranging, including applications in pollution, ecology, hydrology, meteorology and
58 climate change, with research topics motivated by both science and policy-related questions. Ecological applications have
59 included epidemiology (Gulliver et al., 2011), conservation (Hooftman & Bullock, 2012) and modelling spatial distributions
60 for mammals (Croft et al., (2017), insects (Mair et al., 2014), birds (Carrasco et al., 2018), invasive species (Fraser et al.,
61 2015) and pollination (Senapathi et al., *2015;* Baude et al., 2016). Whilst hydrological applications have included assessing
62 impacts of catchment land-use on rivers and lakes (Bussi et al., 2016), determining flood risk (Reynard et al., 2001; FEH,
63 2018) and modelling impacts of farming on water quality (Taylor et al., 2016). Spatial variability in health has also been
64 explored through modelling of hayfever risk (McInnes et al., 2017), air pollution impacts on human health (Stedman et al.,
65 1997) and bovine tuberculosis (Wint et al., 2002). In recent years, the LCM has also been used increasingly for mapping

66 ecosystem service provision (Emmett et al., 2016) and natural capital (Norton et al., 2018), and to aid creation of new data

67 sets such as the UKCEH Land Cover Plus: Pesticides 2012-2017 maps (Jarvis et al., 2020).

68

69 This paper describes the methods and data used to produce the UK Land Cover Map 2021 (LCM2021), as well as the derived

70 LCM2021 data products. LCM2021 was created by classifying satellite data into 21 land cover classes, with these classes

71 based on the UK Biodiversity Action Plan Broad Habitat definitions (Jackson, 2000). The LCM2021 production process

72 involved three stages: pre-processing of input data, image classification and production of the final data products. We present

73 the results of the classification and the validation of 21-class and 10-class versions of the data set. We describe the different

74 data products available and explain how they can be accessed.

2 Input data sets

76 Producing a Land Cover Map requires a range of data sets, typically including satellite data and context data, as well as

77 training and validation data. These data sets are described here, followed by the methods in Section 3.

2.1 Satellite data

79 LCM2021 used Sentinel-2 MultiSpectral Instrument (MSI) Level-2A surface reflectance satellite data (Drusch et al., 2012;

80 Claverie et al., 2018) acquired and pre-processed in Google Earth Engine (Gorelick et al., 2017). The images were acquired

81 between the 1st December 2020 and the 31st January 2022. All 10 and 20 m spectral bands, comprising bands 2 (490 nm), 3

82 (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

83 used.

2.2 Context data

85 Context data were used as additional inputs to the classification process to enable better classification of the required land

86 cover classes (Rogan et al., 2003). The context data included a digital elevation model (DEM), coastline, foreshore and tidal

87 water layers (to aid coastal classification), building and road layers (to reduce confusion between arable and urban areas)

88 (Table 1), and freshwater and forest layers. The DEM was used to calculate slope and aspect, which were also included as

89 context layers. National cartographic products for Great Britain (GB) were provided by the Ordnance Survey (OS), the

90 national mapping agency of GB, whereas for Northern Ireland (NI) products were provided by a number of government

91 organisations including the NI Statistics and Research Agency (NISRA), Ordnance Survey Northern Ireland (OSNI) and

92 the NI Department of Agriculture, Environment and Rural Affairs (DAERA). Slightly different context products were

93 available for NI compared to GB (Table 1). The main difference between the OS NI and OS GB context data, is the lack of

94 a NI equivalent to the GB buildings layer. The OS layers were converted from vector to raster data, with distance from

95 layers created for buildings, roads, rivers and water bodies. Distance from products were used to allow the context data

96 products to influence a wider area, rather than just the pixels they intersected with. The 10 m NEXTMap Digitial Elevation
97 Model (DEM) was used to calculate slope and aspect, with all three included as context layers.
98
99 **Table 1:** Context data set details, including comments on accessibility, data quality and timeliness. [1] Slope and aspect were
100 derived from the DEM data. Abbreviations: Great Britain (GB), Northern Ireland (NI). [2] data used subject to licensing
101 conditions, [3] data used under an open license. Ordnance Survey GB open data from: https://osdatahub.os.uk/, Ordnance
102 Survey NI data from: https://www.nidirect.gov.uk/articles/osni-open-data-product-list, NI Statistics and Research Agency
103 data from: https://www.opendatani.gov.uk/dataset/settlement-development-limits-2015, DAERA data sets from:
104 https://www.daera-ni.gov.uk/articles/wmu-digital-dataset-downloads, Copernicus Land Monitoring Service data sets from:
105 https://land.copernicus.eu/pan-european/corine-land-cover/clc-2012.

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]	10m 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 include 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 Datasets
Water	Distance from water used to improve classification of	GB	OS [3]	Open Map Local, surface water area polygons

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	habitats often associated with proximity to rivers (e.g. Fen, Marsh and Swamp, and Neutral Grassland).	NI	DAERA [3]	Rivers Digital Datasets – River segments; Lakes Digital Datasets – 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

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 section 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., *2011,*). The spatial framework was first generated for LCM2007 and revised for LCM2015 onwards, by fixing some minor spatial errors and additional simplifications of land parcel structure. The spatial framework is used to derive a land parcel dataset from which 25 m and 1 km raster datasets are generated.

2.5 Validation data sets

Validation data are necessary to establish the accuracy of land cover classifications (Foody et al., 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) was 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) checked against current (circa-2021) aerial photography to ensure no change

129   had occurred, some additional manually derived points (interpreted from aerial photography) were also added, particularly
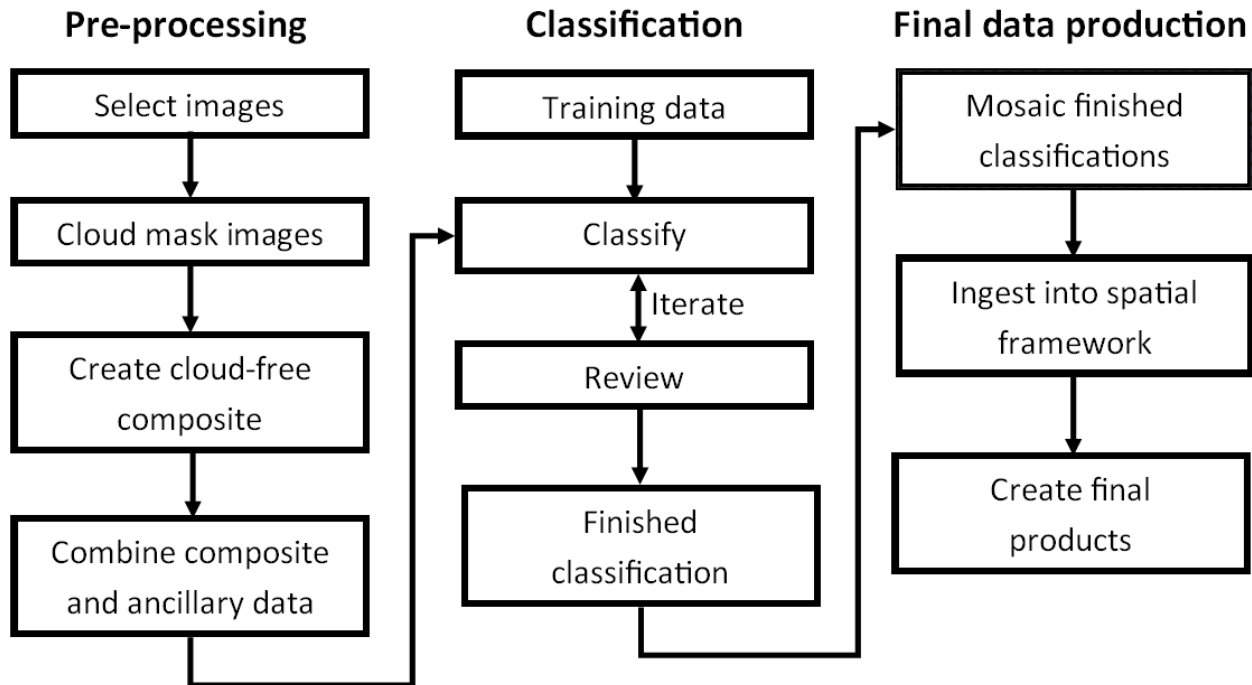130   for water and urban-classes.

131
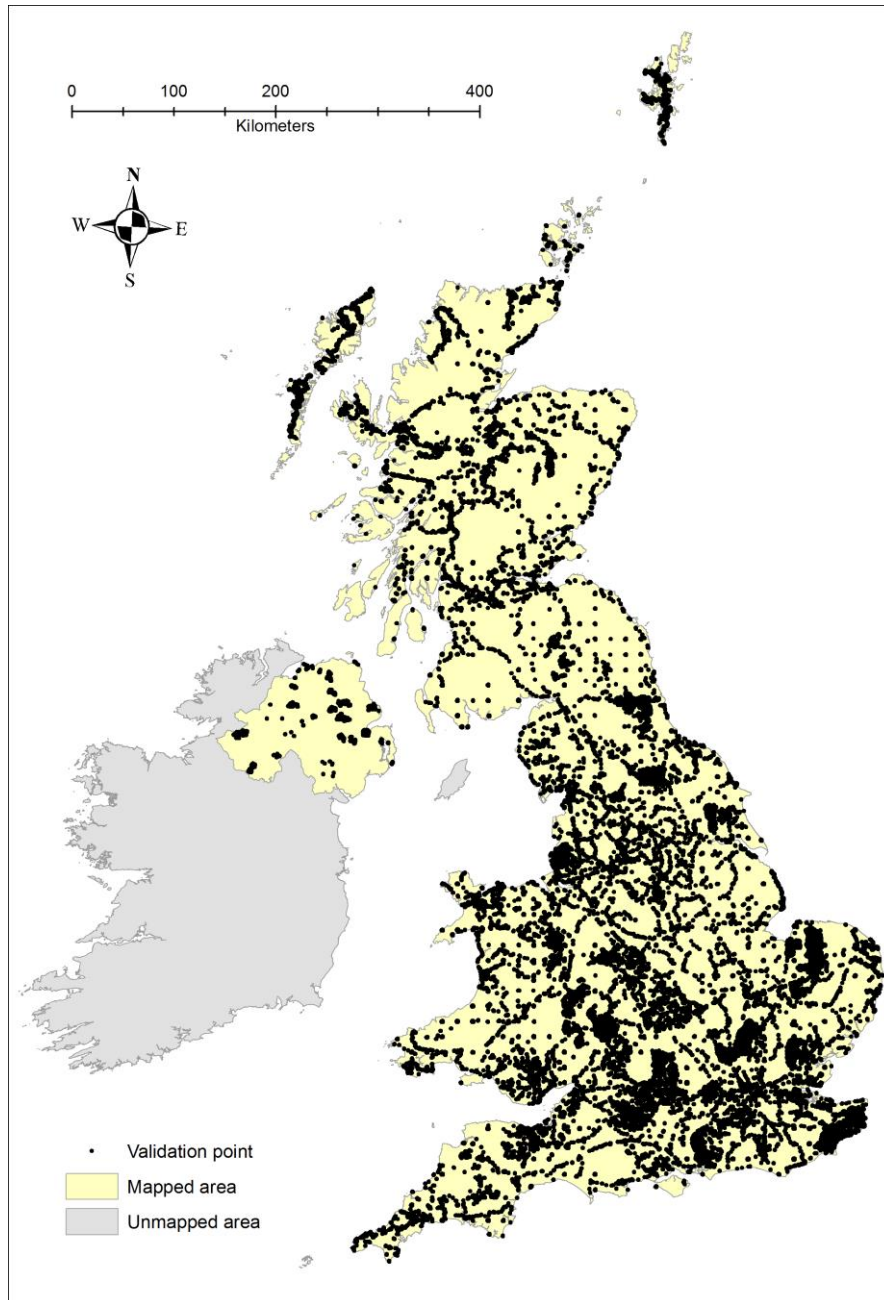
132
133   **Figure 1: Distribution of the 35,182 validation points for LCM2021.**

134   **3 Methods**

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

136   of data products.

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138

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

140

141   **3.1 Composite image creation**

142   Temporal composite images (also known as temporal aggregations) are increasingly used to compress voluminous image

143   collections and overcome problems of data gaps caused by clouds in optical imagery (Carrasco et al., 2019; Holben, 1986).

144   Cloud computation platforms, such as Google Earth Engine (Gorelick et al., 2017), provide users with tools to create

145   composite images aggregated over user-defined intervals (e.g. annually, monthly, bi-monthly) and for user-defined

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

147

148   Seasonal composites images of Sentinel-2 Multi-Spectral Instrument (MSI) Level 2-A data (Drusch et al., 2012) were

149   created using Google Earth Engine, with cloud-masking based on the Sentinel-2 Cloud Probability layer, s2cloudless

150   (Skakun et al., 2022) and snow-masking based on the QA attributes performed. Images representing median surface

151   reflectance were aggregated over four composite periods; 1st Dec 2020 - 31st March 2021; 1st April 2021 – 30th June 2021;

152 1st July 2021 – 31st September 2021; and 1st October 2021 – 31st Jan 2022. Periods one and four were extended by a month

153 into the previous and following years to reduce cloud effects. Seasonal composites were used as they capture the variability

154 in vegetation phenology through the year, which aids separation of the different land cover classes (Carrasco et al., 2019),

155 and for the UK, aggregation of Sentinel-2 data for four seasons provides data for all four seasons in over 99.9% of pixels

156 (see SI). Context layers including slope, aspect, elevation distance to coast, distance to building, distance to road, distance

157 to freshwater, plus a foreshore mask, tidal water mask and a forest mask (GB only) were integrated with the composite

158 period satellite imagery (see Table 1 for details of the context data layers, which varied slightly between GB and NI). The

159 addition of context layers reduces spectral confusion between different classes with similar spectral characteristics. The

160 seasonal composites, with the added context data, were then classified.

161 **3.2 Classification**

162 LCM2021 is based on the 21-class nomenclature presented in Table 2. The 21 Land Cover classes are based on UK Broad

163 Habitat definitions (Jackson, 2000) and are designed to cover the range of habitats found in the UK that can be reliably

164 mapped from satellites. Detailed descriptions of the classes are given in Appendix 1. Production of the classifications is split

165 into two stages, first developing the core training areas (section 3.2.1), and second the classification process (section 3.2.2).

166

167 **Table 2. Relationship between the 21 LCM2021 classes, the 10 Aggregate classes and the underlying Broad Habitat classes. Italic**
168 **text highlights classes meeting the Broad Habitats classes as documented in Jackson (2000). [1,2] LCM2021 and Aggregate class**
169 **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

8

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	

3.2.1 Core training areas

Selecting appropriate training areas is crucial for 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 dataset undergoing edits where required to produce the final classification.

When selecting training polygons from this spatial framework, as well as identifying polygons classified as the same land cover class for LCM2018/19/20, 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 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 because of changes in land cover. Systematic visual checks of the training 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 bias towards common classes and rare classes may be lost from results completely. Balance was achieved by bagging all training pixels

193   per class, then from each bag sampling 10000 pixels with replacement. For each pixel the balanced RF classifier yields a

194   probability of membership for all 21 land cover classes. Land cover per pixel is assigned by highest probability.

195

196   **3.3 Product construction**

197   Classifications for all tiles were compiled into a full UK spatial coverage at 10 m pixel resolution. This produced a two-

198   band image. Band one is the most likely land cover; band two the probability associated with this land cover, but rescaled

199   into a integer over the interval 0 to 100. Rescaling to an integer enables classification results to be stored in 8-bit, thereby

200   reducing data size without degrading information. The 10 m raster is the precursor for all derived products.

201

202   The ingestion into the spatial framework involved determining the majority (modal) class for each polygon. Separate GB

203   and NI data sets were created to accommodate the different map projections. Figure 3 shows the extents of the 32 composites

204   used to achieve complete coverage of the UK. The approximate 100x100 km tile size, based on a modified version of the

205   Ordnance Survey 100 km tile grid was chosen as this provides a manageable size for processing. Some tiles such as those

206   encompassing the Western Isles, Orkney and Shetland, and Cornwall and the Scilly Isles are intentionally enlarged to avoid

207   a sparsity of training data due to the extensive presence of sea in these tiles. Occasionally where tile extents are modified,

208   overlap between adjacent tiles does occur.

209
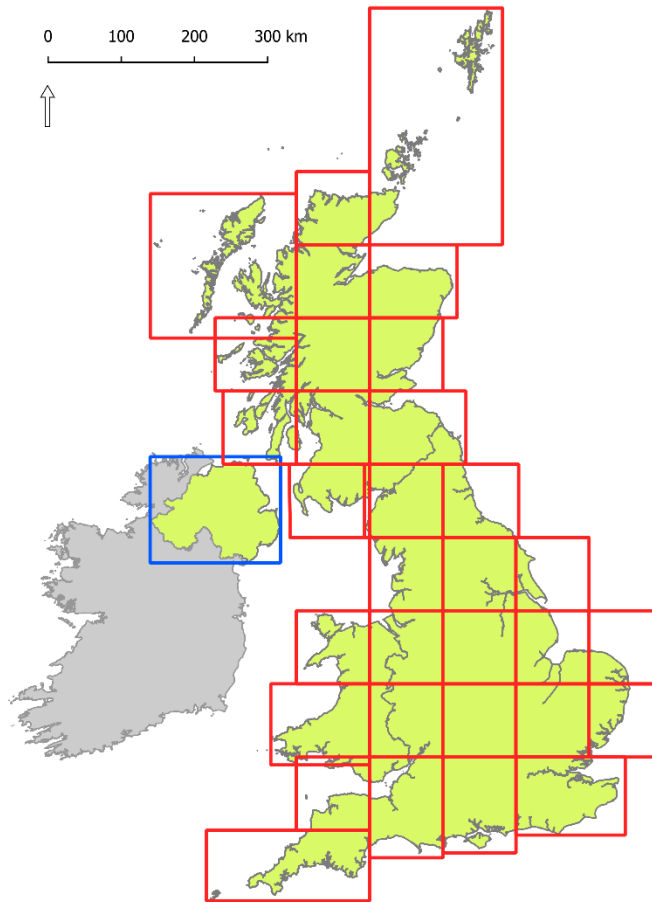
Figure 3: Composite images extents comprising LCM2021 for Great Britain (red) and Northern Ireland (blue).

Once the GB and NI classification mosaics were complete, a series of minor knowledge-based corrections were applied. These included 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 being misclassified inland using a coastal mask.

3.4 Validation

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

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 (highlighted in green in Table 3), 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 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 section 5 for more details about the aggregate class products) the validation suggests an overall accuracy of 86.5% (Table 4).

Table 3. Confusion matrix for LCM2021 against 35,182 reference points. The main diagonal is highlighted green. BW = Broadleaved woodland; CW = Coniferous woodland; AR = Arable; IG = Improved grassland; NG = Neutral grassland; CG = Calcareous grassland; AG = Acid grassland; FMS = Fen, marsh, swamp; H = Heather; HG = Heather grassland; B = Bog; IR = Inland rock; SW = Saltwater; FW = Freshwater; SLR = Supra-littoral rock; SLS = Supra-littoral sediment; LR = Littoral rock; LS = Littoral sediment; SM = Saltmarsh; U = Urban; SU = Suburban; PA = Producer's accuracy; UA = User's accuracy; OA = Overall accuracy.

Classified Data	Reference Data																					Total	UA (%)
	BW	CW	AR	IG	NG	CG	AG	FMS	H	HG	B	IR	SW	FW	SLR	SLS	LR	LS	SM	U	SU		
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	10102	306	28	1	2	0	0	3	1	10	0	6	0	0	0	0	1	13	13	10511	**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	11370	5969	820	1076	1703	638	974	844	1184	198	82	595	62	245	107	267	180	2709	3087	35182	
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												

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241
242
243 **Table 4: Confusion matrix for LCM2021 aggregate classes against 35,182 reference points. The main diagonal is highlighted**
244 **green. BW = Broadleaved woodland; CW = Coniferous woodland; AR = Arable; IG = Improved grassland; SNG = Semi-natural**
245 **grassland; MHB = Mountain, heath and bog; SW = Saltwater; FW = Freshwater; C = Coastal; BU = Built-up and gardens; PA =**
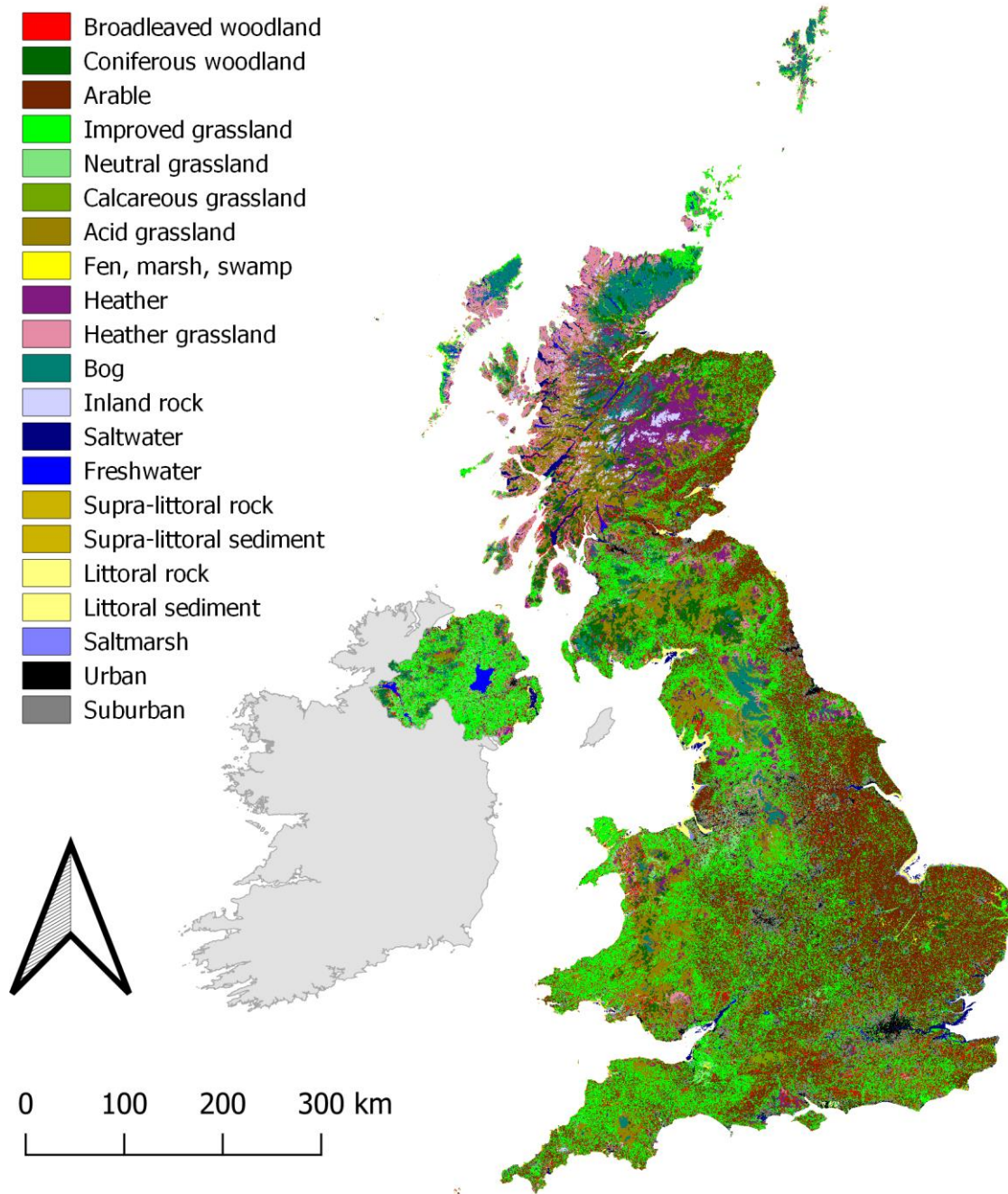246 **Producer's accuracy; UA = User's accuracy; OA = Overall accuracy.**

Classified Data	Reference Data										Total	UA (%)
	BW	CW	AR	IG	SNG	MHB	SW	FW	C	BU		
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	10102	306	31	14	0	6	1	26	10511	**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**

13

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	11370	5969	4237	3200	82	595	861	5796	35182	
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**						

247

4.2 LCM2021 map

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

Legend:

- Broadleaved woodland
- Coniferous woodland
- Arable
- Improved grassland
- Neutral grassland
- Calcareous grassland
- Acid grassland
- Fen, marsh, swamp
- Heather
- Heather grassland
- Bog
- Inland rock
- Saltwater
- Freshwater
- Supra-littoral rock
- Supra-littoral sediment
- Littoral rock
- Littoral sediment
- Saltmarsh
- Urban
- Suburban

0   100   200   300 km

252

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

15

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.

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	21045	12322	5330	2555	838
2	Coniferous woodland	13830	2788	9022	1422	598
3	Arable	49121	41867	5960	841	453
4	Improved grassland	66394	39304	13053	7765	6272
5	Neutral grassland	4200	1659	105	525	1911
6	Calcareous grassland	2561	2387	31	11	132
7	Acid grassland	21873	4448	12281	4404	740
8	Fen	783	471	68	182	62
9	Heather	11562	2081	8636	566	279
10	Heather grassland	11842	1433	9719	409	281
11	Bog	10457	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	17539	13669	1812	1308	750
	Total area (km^2)	246902	132651	78949	20927	14375

5 LCM2021 data products

LCM2021 is provided in a range of open data formats and at 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., 2021a, 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., 2021 c, 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., 2022 e, 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; Morton et al., 2014) and LCM2015 (Rowland et al., 2017a, b); LCM2000 (Fuller et al., 2002 a, 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 British National Grid projection (EPSG:27700) and the Northern Ireland data in the Irish National Grid projection (EPSG:29903).
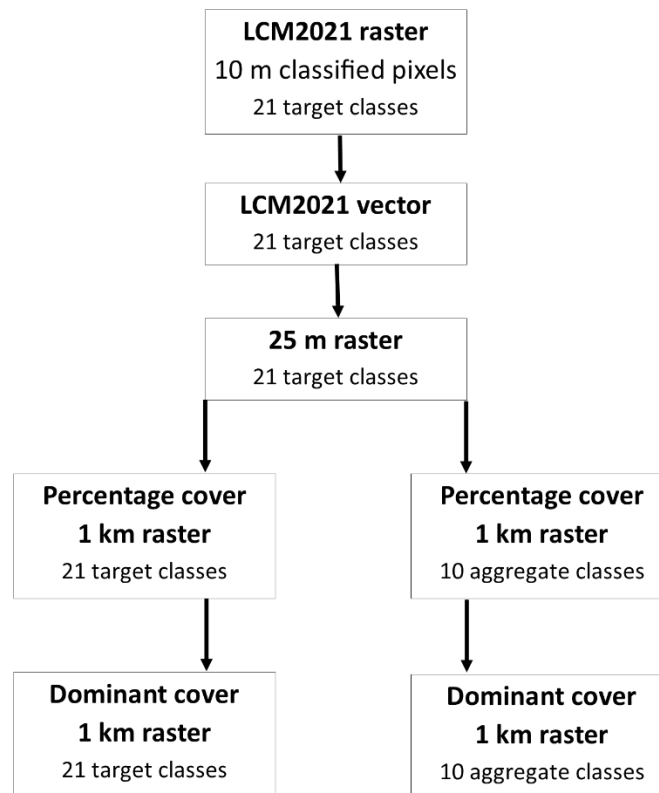
Figure 5: Overview of the LCM2021 data set production process. The vector version of the data set is constrained by licensing restrictions due to the inclusion of national mapping agency data

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278

279 LCM2021 is produced in a range of spatial resolutions (Fig. 6) to support different types of analysis. The 10 m data set is a

280 relatively new data set (first produced in LCM2020) and enabled by the 10 m resolution of the optical Sentinel-2 bands. The

281 higher spatial resolution products capture the fine detail of the landscape and are often used for assessment of landscape

282 features requiring fine resolution, such as habitat connectivity (Hooftman & Bullock, 2012) or for detailed studies of small

283 areas (e.g. Miller et al., 2020). The 1 km data sets are primarily used for national-scale modelling, often in conjunction with

284 a range of other coarser resolution environmental data sets (e.g. Coxon et al., 2020; Jordan et al., 2022) and are useful for

285 showing the distribution of a particular class across the UK. For example, Fig. 7 shows the distribution of the broadleaf

286 woodland class and the urban class from the aggregated 1 km percentage data sets for the UK.
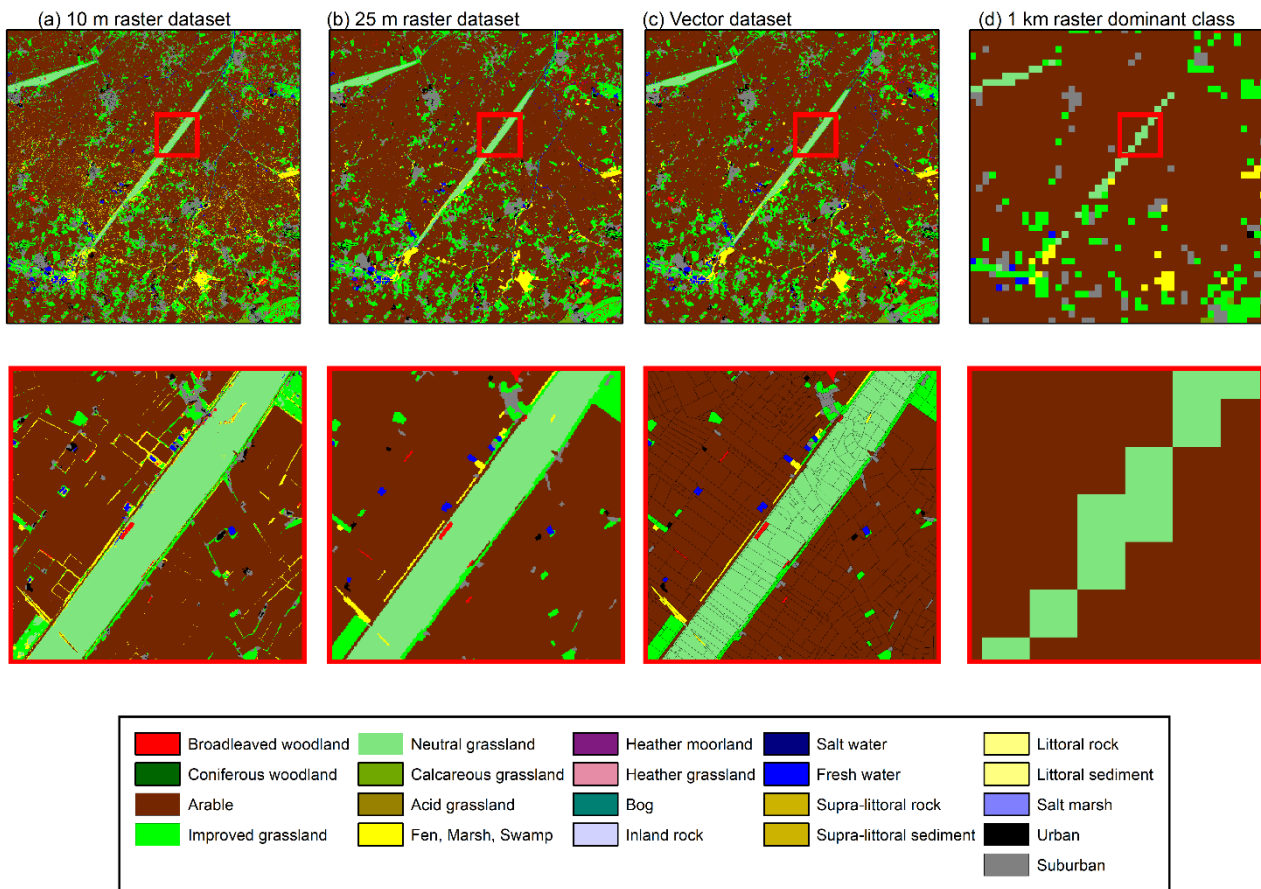
287

288 **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,**
289 **and; (d) 1 km raster data sets. Top panels shows zoomed out view, red box shows the location of the zoomed in area in the lower**
290 **panels.**

291

292
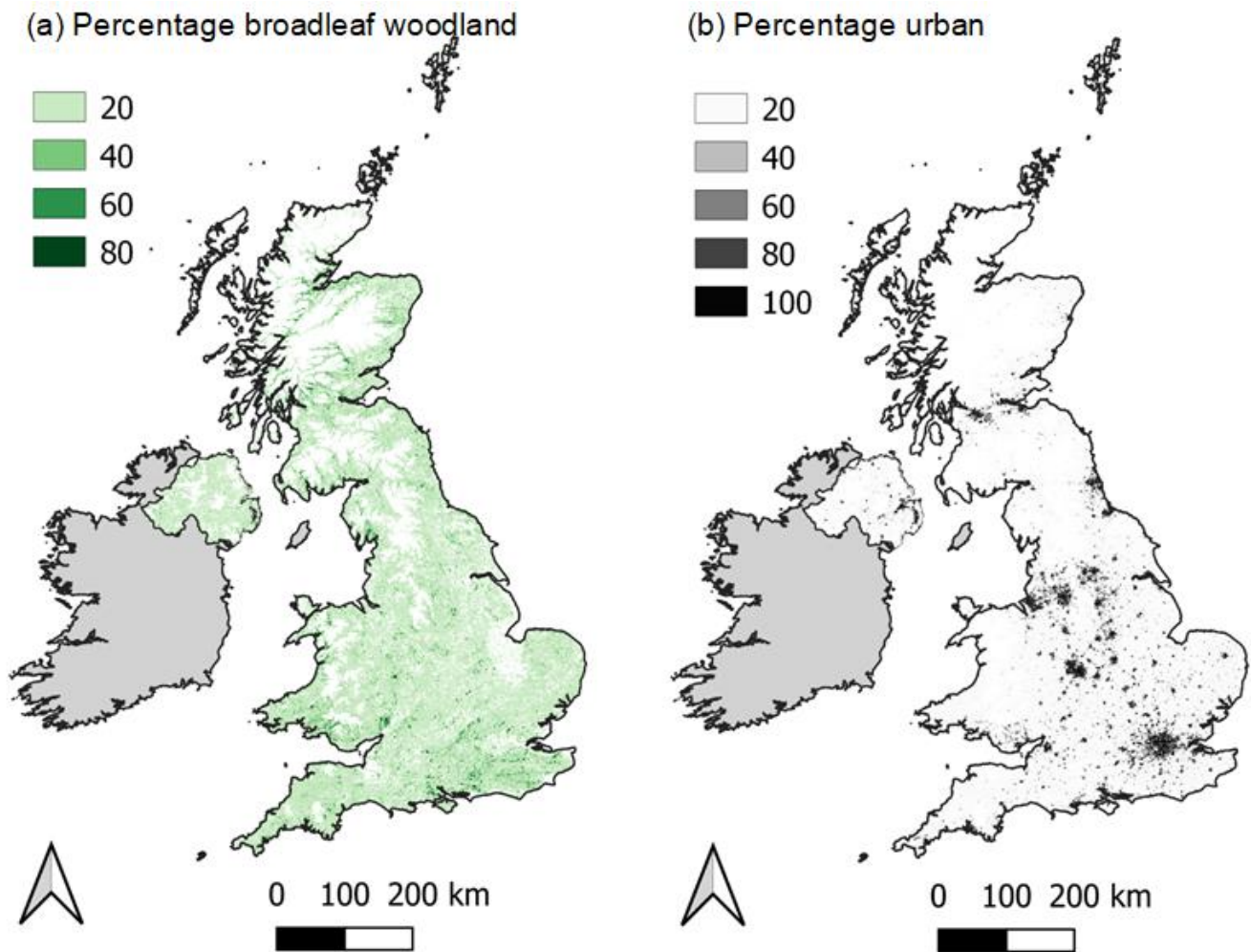
Figure 7: Examples of the UK-wide distribution of (a) Broadleaf woodland and (b) Built-up areas and gardens percentage cover, based on the 1 km aggregate class percentage data sets for GB and NI (Marston et al., 2021g).

6 Data availability

The LCM2021 data products (Table 6) have digital object identifiers (DOI) and are available via the NERC Environmental Data Service (https://eds.ukri.org/environmental-data-service), with all versions listed on the LCM2021 data collection page (UKCEH, 2022a). Raster data are provided as uncompressed GeoTiffs and are supplied with data set documentation, and QGIS files for displaying the classifications in the LCM-standard palette (used since LCM2000) (see Appendix B, B1 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 (UKCEH, 2022b).

19

304 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)

305

306 All LCM raster datasets are available under a single common licence without charge for non-commercial use which includes

307 non-commercial research and use within public bodies and charities and their contractors. Alternative licensing can be

308 arranged on request with commercial organisations who wish to use the datasets within their own internal business

309 operations or to develop commercial products or services.

310 **7 Conclusion**

311 The UK Land Cover Map series, comprising LCM1990 (formerly LCMGB) (Fuller *et al*,. 1994), LCM2000 (Fuller et al.,

312 2002c), LCM2007 (Morton et al., 2011), LCM2017, LCM2018, LCM2019 and LCM2020 underpin a wide range of UK

313 environmental science analysis and LCM2021 is expected to continue this trend. The accuracy of LCM2021 varies with

314 class, but it has an overall accuracy of 82.6% for the 21 target classes and 86.5% for the 10 aggregate classes.

315

316 **Author contribution:** DM and CR acquired funding. CM, CR and DM pre-processed the data and conducted classifications.

317 DM designed and implemented the Random Forest classification software and supporting computation structures with input

318 from the whole team. CR, DM and CM developed code for pre-processing the satellite data. CM, CR and AO reviewed the

319 classifications. CR, CM and AO prepared the validation data. CR and CM prepared the manuscript with contributions from

320 all co-authors, DM, CR and CM designed the project. CM led the production of LCM2021.

321 **Competing interests**

322 The authors declare that they have no conflict of interest.

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568

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
description of the underlying Broad Habitat classes.

LCM2021 land cover class	Notes
Broadleaved woodland	In the UK BAP *Broadleaved, mixed and yew woodland* broad habitat definition (Jackson, 2000) the broadleaved woodlands are characterised by stands >5 m high with tree cover >20%. Scrub (<5 m) requires a cover >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 occurring 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 >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 maybe 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, 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 >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 plantation and recently felled areas. These are land use, not land cover. Newly felled areas are often dominated by grass, heather and encroaching vegetation and more likely to be classified as these, instead of coniferous woodland. Deciduous larch has potential for confusion with broadleaved deciduous woodland but is generally correctly identified.
Arable and horticulture	The BAP Broad Habitat *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 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 *Neutral grassland* is expected to be challenging for satellite-based classification. BAP *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	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/soil type layer, which we would expect to help further. For regions know to contain substantial coverage of Calcareous Grassland, for example Limestone Dales of Derbyshire and North Yorkshire, the South Downs and Salisbury Plain our results match expectations.
Acid grassland	The UK BAP *Acid grassland* can be spectrally variable, depending on dominant species composition. Deciduous acid grassland, dominated by *Molinea caerula* has a distinct signal from acid grasslands dominated by mixtures 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 understory. 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* into two classes, depending on the density of heather, producing the heather and heather grassland classes (it is heather when there is greater than 25 % Heather Cover). This was to retain some consistency between the LCM1990 and LCM2000 classes 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: 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.
Fen, marsh and swamp	The UK BAP *Fen, marsh and swamp* includes fen, fen meadows, rush pasture, swamp, flushes and springs. From a remote sensing perspective fen, marsh and swamp is problematic as it is can be comprised of a wide range of vegetation types and many patches are below the MMU of the UKCEH land parcel spatial framework. The small size of many fen, marsh and swamp patches, plus their typically mosaic nature make it difficult to find reliable training data. Consequently, fen, marsh and swamp 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 *Bog* includes ericaceous, herbaceous and mossy swards in areas with a peat depth >0.5 m. We cannot detect peat depth from satellites. Vegetation on deep peat soils represent 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 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, so is a good indicator of where bog is likely to be occurring. However, bog and the range of upland vegetation classes expected to occur on peaty soils (acid grassland, fen marsh and swamp, heather, and heather grassland), potentially causing interclass confusion. This is partly due fine-scale variation but largely an effect of ambiguous definitions. 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 not 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 high priority.
Freshwater	The UKCEH Freshwater class comes from merging two BAP BHs (*Standing open water and canals,* and *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 so effectively disappear into the dominant surrounding vegetation. Where these features are appropriately aligned and sufficiently wide, pixels they may be detected and if so will be available in the Raster Classification datasets.
	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 *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. Areas of coastal sand may be confused between this class and the littoral sediment class. Supralittoral 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 supralittoral rock and thus more readily detected using satellite images.
Littoral sediment; and saltmarsh	The BAP Broad Habitat *Littoral sediment* has a subclass, the BAP Priority Habitat *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, when we mistake other vegetation in the coastal zone (mainly Arable) as saltmarsh.
	The littoral sediment is sometimes confused with the supra-littoral sediment class.

572

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.

576

577 **Table B1: Standard LCM colour palette.**

Land cover class	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

578

579 **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

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581

Land cover classes

- Broadleaved woodland
- Coniferous woodland
- Arable
- Improved grassland
- Neutral grassland
- Calcareous grassland
- Acid grassland
- Fen, Marsh and Swamp
- Heather and shrub
- Heather grassland
- Bog
- Inland rock
- Saltwater
- Freshwater
- Supralittoral rock
- Supralittoral sediment
- Littoral rock
- Littoral sediment
- Saltmarsh
- Urban
- Suburban
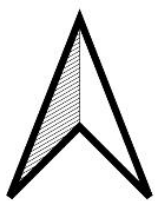
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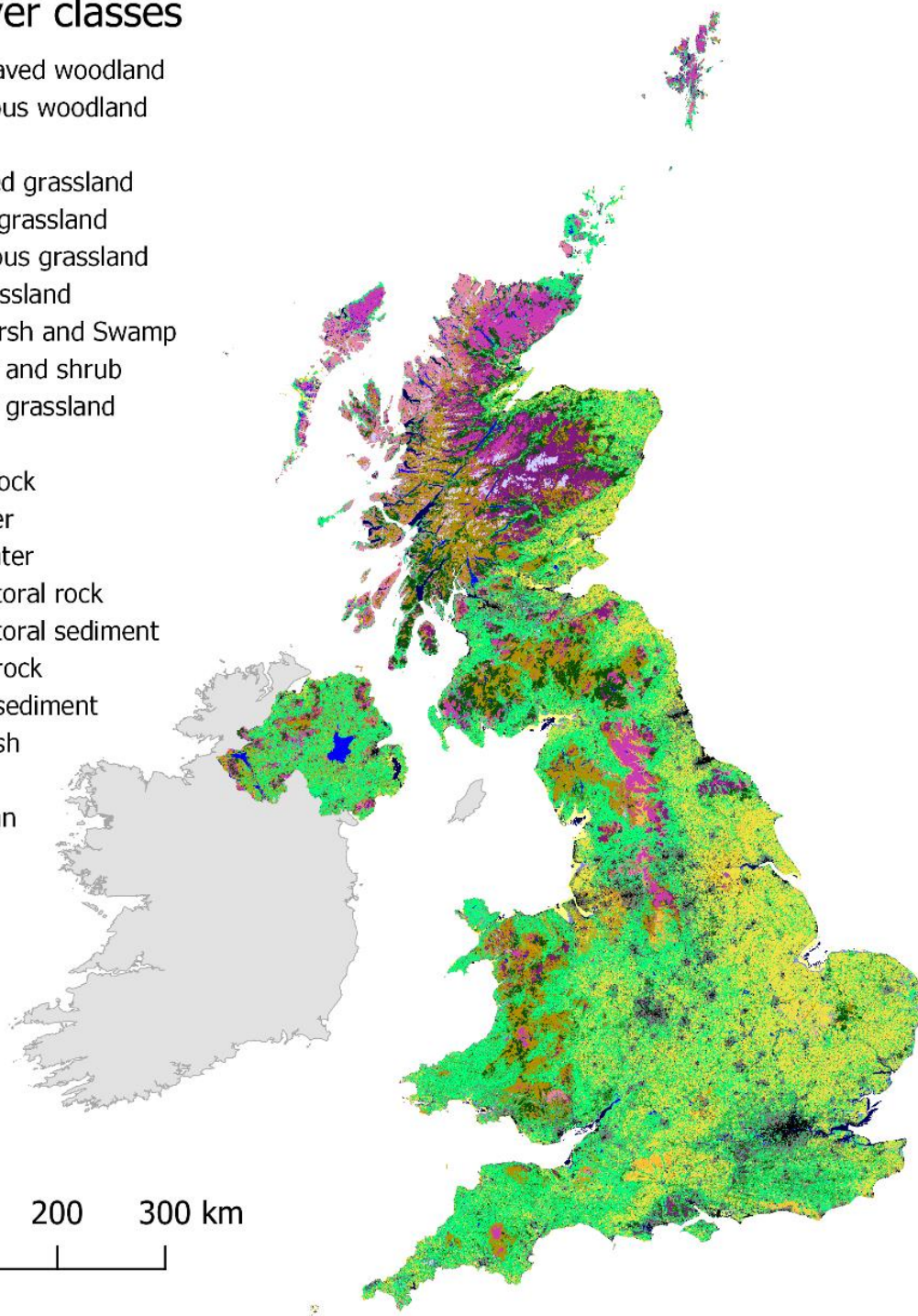
582

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