Published online March 12, 2007

Mapping Peatlands in Ireland using a Rule-Based Methodology and Digital Data

John Connolly*
Nicholas M. Holden
Shane M. Ward
Biosystems Engineering
School of Agric., Food Sci. and Vet. Medicine
Univ. College Dublin
Earlsfort Terrace
Dublin 2
Ireland

Peatlands have been recognized as being an important global C pool and make significant contributions to national C fluxes. In Ireland, they cover a considerable amount of the national land area, but no recent inventory or mapping has been undertaken to quantify the spatial extent of this important resource. This study used a rule-based methodology implemented as a series of hierarchical rules in ArcGIS to estimate the extent of contemporary peatlands in Ireland from soil and land-cover maps dating from the 1970s, 1980s, and 1990s. The Derived Irish Peat Map was produced at a pixel resolution of 100 m and shows Ireland's peatland resource to be 0.95 Mha or 13.8% of the national land area. This is comparable to estimates of 13.2% from CORINE land-cover data (1990s), 17.0% from the Peatland Map of Ireland (1970s), and 16.7% from the General Soil Map (1980s). The derived map depicts the spatial extent of three peatland types: raised bog and low- and high-level blanket bog. Ground truthing of the derived map enabled estimates of pixel reliability to be calculated. The derived map has an overall reliability of 75% compared with the reliability of 65% for CORINE, 58% for the Peatland Map of Ireland, and 50% for the General Soil Map. We concluded that the methodology created a value-added soil map product from a number of data sources, all of which were to some degree imperfect. The approach taken could be applied to similar survey problems not related to peatlands.

Abbreviations: CORINE, Coordination of Information on the Environment; DIPM, Derived Irish Peat Map; DTM, digital terrain map; GIS, geographic information system; GSM, General Soil Map; HLM, high-level montane; LLA, low-level Atlantic; PAVC, peat-associated vegetation class; PM, Peatland Map of Ireland; PSA, peat soil association; RB, raised bog.

In 2002, Ireland signed the Kyoto Protocol (Wissema and Matthews, 2003). One of the main aims of the Kyoto Protocol is to stabilize and reduce greenhouse gas concentrations in the atmosphere (Worrall et al., 2003) by reducing fossil fuel emissions and increasing biotic or terrestrial sinks for C (Waddington and Warner, 2001). Janssens et al. (2005) stated that terrestrial C sequestration substantially mitigates global warming, at least in the short term. The European Union (EU) has agreed to cut its combined emissions to 8% below 1990 levels by 2008 to 2012 (Gugele and Ritter, 2000). Ireland was allowed to increase its emissions to 13% above 1990 levels; these had risen, however, to between 23 and 28% of 1990 levels in 2004 (Bergin et al., 2004). To achieve the agreed target for emissions, Ireland will now have to enter a phase of very active emission reduction and try to maintain or increase legitimate C sinks.

As a part of the EU strategy to reduce emissions, each member state must produce, on an annual basis, a report of anthropogenic CO_2 emissions by sources and removals by sinks (Gugele et al., 2003). The main source categories are classified as energy, agriculture, industrial processes, and waste, while legitimate sinks include forests and other ecosystems that absorb C (Gugele et al., 2003; European Environment Agency, 2005). Peatlands have been recognized as making significant contributions to national C fluxes (Tolonen and Turunen, 1996; Clymo et al., 1998). They are not at present counted as terrestrial sinks, however (Roulet, 2000). The reason for this is that the source–sink status of a peatland is both spatially and temporally variable (Griffis et al., 2000; Arneth et al., 2002; Kuhry and Vitt, 1996; Bubier et al., 1998; Smith et al., 2004). Despite these issues, peatlands are a very important, and dynamic, global C pool (Gorham, 1991) and much effort is now focusing on better understanding their response to weather (Alm et al., 1997; Blodau, 2002), their long-term relationship with climate (Thormann et al., 1998; Frolking et al., 2002; Belyea and Malmer, 2004), their spatial extent and function globally (Matthews and Fung, 1987; Sheng et al., 2004), and their function and extent at national scales (Vitt et al., 2000; Gajewski et al., 2001; Sippola and Yli-Halla, 2005; Proctor, 2005).

To evaluate the role of Irish peatlands within the national C budget, it is necessary to have a reliable estimate of their spatial extent and function. In this study, a rule-based decision tree methodology was developed, based on geographic information system (GIS) map algebra and Boolean logic, that can be used for integrating national-scale soil and land resource map data to estimate the spatial extent of peatland by type and disturbance. As new resource surveys become available they can be processed using the methodology, and the approach could be used for any soil mapping task that requires making a best spatial estimate from multiple, possibly flawed, map data.

The mapping of peatlands has always been a difficult endeavor. Vitt et al. (2000) used classification and aerial photography to determine peatland distributions. In their 1996 inventory of lowland raised bogs in Great Britain, Lindsay and Immirzi (1996) used three classes of bog: primary, secondary, and archaic. This classifica-

Soil Sci. Soc. Am. J. 71:492–499
doi:10.2136/sssaj2006.0033
Received 23 Jan. 2006.
*Corresponding author (john.connolly0@ucd.ie).

tion system was used to calculate the extent of natural, degraded, and drained areas (Lindsay and Immirzi, 1996). Milton et al. (2005) used high-resolution multispectral data and information on bog surface microrelief to create a peatland classification map. Talkkari and Nevalainen (2003) used GIS techniques and ArcMap software (ESRI, Redlands, CA) to combine multisource data consisting of soil maps of different scales and numerous other data to create a soil database for Finland (Sippola and Yli-Halla, 2005). Peatlands in Northern Ireland were mapped using aerial photographs (Cruickshank and Tomlinson, 1990). Irish peatlands were mapped in the 1970s using field surveys and the amalgamation of older maps, resulting in the Peatland Map of Ireland (Hammond, 1979). They also appear on a national-scale soil association map (Gardiner and Radford, 1980a), but often the exact spatial distribution cannot be determined from this map. Peatlands also appear as a land cover class on the Coordination of Information on the Environment (CORINE) products (O'Sullivan, 1994; Brossard et al., 2000). All available data sources in Ireland are to some degree flawed and cannot be regarded as a reliable baseline of the extent of peatlands.

Irish peatlands are conventionally classified as fens, raised bogs, and blanket bogs (Hammond, 1979; Feehan and Donovan, 1996). A bog is a surface covered in peat that receives its nutrients only from the rain (Bellamy, 1986; Charman, 2002; Schouten, 2002). Raised bogs occur predominantly in the center of Ireland (Feehan and Donovan, 1996), and can be further subclassified into true midland, transitional, or industrial types depending on location and anthropogenic use (Hammond, 1979). Blanket bogs cover large areas of the western seaboard and upland areas and hence have been classified into low-level Atlantic (LLA) blanket bogs and high-level montane (HLM) blanket bogs by Hammond (1979). Fens are peatlands that receive nutrients from surface and groundwater as well as rainfall, and are now very rare, covering just 19 607 ha in Ireland (Charman, 2002; Crushnell, 2005). Due to the very limited extent of fens, no explicit attention was addressed to fens in this study.

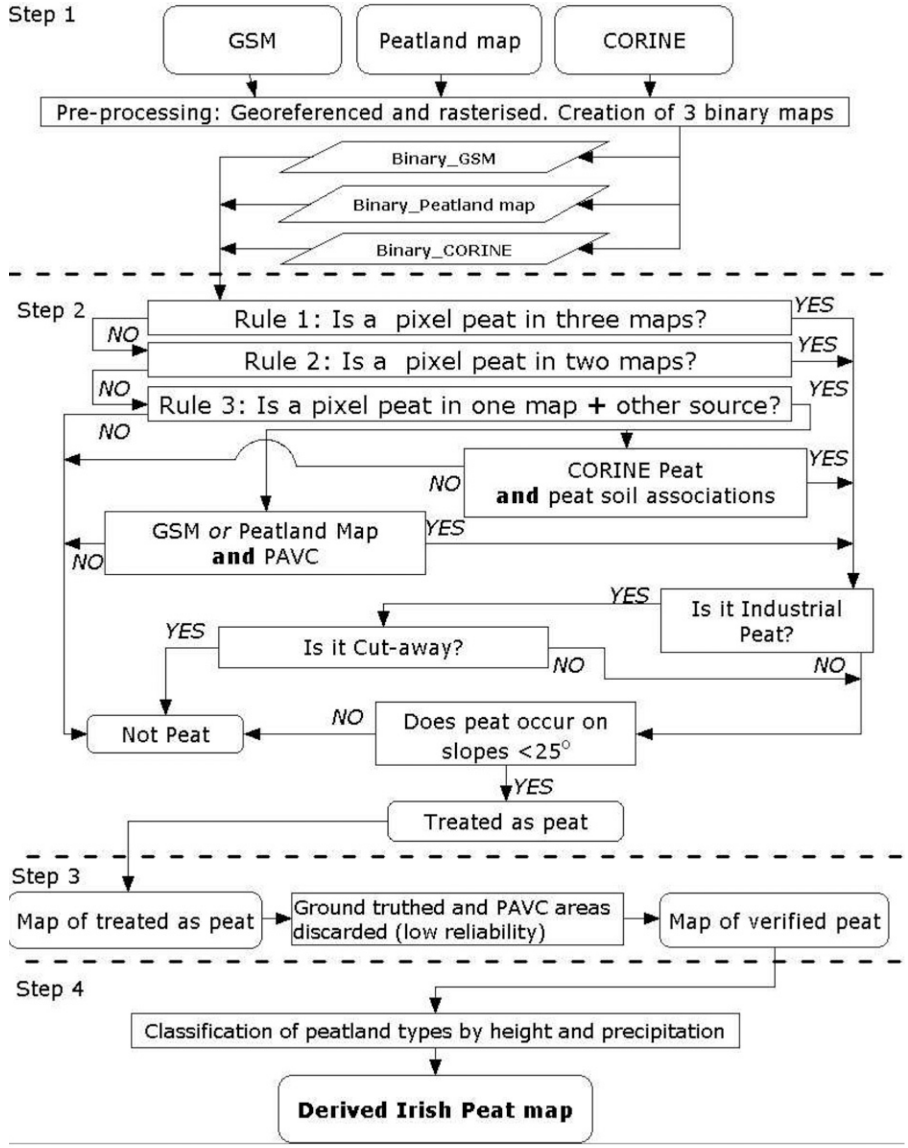

Fig. 1. Rules-based methodology Steps 1 through 4; GSM = General Soil Map, PAVC = peat-associated vegetation class.

The objective of the study was to devise a method that would permit the best estimate of the spatial extent of peatlands in Ireland to be made using combinations of existing data sources. A rule-based decision tree was implemented in a GIS to determine locations with a high likelihood of being peat, and to classify the peat into three types: raised bog (RB), HLM blanket bog, and LLA blanket bog. The methodology was formulated so that as new resource data become available, they can be integrated to make improved spatial estimates.

MATERIALS AND METHODS

Step 1: Digital Data Sources and Preprocessing

Three digital maps were available at the time this study was conducted: the Peatland Map of Ireland (PM; Hammond, 1979), CORINE (O'Sullivan, 1994), and the General Soil Map (GSM) (Gardiner and Radford, 1980b; Fig. 1). The PM presents several classes of peat including blanket and raised bogs and areas of industrial peat use. For the purposes of this study, RB was defined as including true midland-type raised bogs, transitional raised bogs, and anthropogenically modified raised bogs, while blanket bogs were subdivided into HLM and LLA types after Hammond (1979).

CORINE is the only national land cover map available for Ireland and is based on interpretations to identify different land cover types either by eye or using computer-assisted interpretation to reveal extra details and resolve ambiguities (Ordnance Survey of Northern Ireland, 1994). The land cover map used was produced in 1990 as part of a Europe-wide project. It has 33 land classes relevant to Ireland, with peatlands being defined as "peat bogs." CORINE is not a soil map and therefore peat soils with vegetation cover such as grassland or coniferous forest are not classified as peat. At the time this study was conducted, a revised CORINE map was being produced but it was not available for use.

The GSM used in this survey was published in 1980 (Gardiner and Radford, 1980b). The map provides a representation of 10 soil associations, including two referenced as peat: blanket peat and basin peat (raised bog) (Coulter et al., 1998). There are also a number of soil associations that the legend indicates contain between 5 and 75% peat, but these are not spatially explicit with respect to the location of the peatlands on the map. The map is based on field surveys at various scales, aerial photographic interpretation, and geological maps (Coulter et al., 1998) and, as such, is not uniform in its precision.

Each map was georeferenced and converted from a vector map into a raster image (Zeiler, 1999) with a pixel resolution of 100 m. Georeferencing is the process of establishing a relationship between a raster's coordinate system and a real world coordinate system (Zeiler, 1999; Bonham-Carter, 1994). Initially, the CORINE map was georeferenced to the Irish National Grid (a Transverse Mercator projection) (O'Sullivan, 1994) by selecting common points of reference such as road or river junctions (Zeiler, 1999). Subsequently, both the GSM and PM were georeferenced to CORINE to allow each map to be standardized in the Irish National Grid projection. It was difficult, however, to accurately georeference the source GSM digital data; therefore >60 points of reference or *tic points* (Zeiler, 1999) throughout Ireland were needed. Before the PM could be rasterized, minor problems identified in its attributes were corrected. Each map was rasterized and reclassified as a binary map (Fig. 1; Arctur and Zeiler, 2004), i.e., 1 and 0 indicating peatland and nonpeatland pixels, respectively.

Step 2: Rule-Based Decision Tree and the Resulting Derived Peat Map

The concept behind the methodology presented was to use raster data (pixels) and that at least two sources of evidence should be present for a pixel to be classified as peat. A rule-based decision tree was then designed for use within a GIS (Fig. 1). The decision tree takes data from the best three digital map sources available (at the time of the study: PM, CORINE, and GSM) and examines them in combination with one another to extract the pixels with a maximum likelihood of representing peatland. As new data sources become available they can be integrated into the analysis process.

The decision tree functions as a filtering system based on Boolean logic, using sequential rules to isolate pixels that are likely to be peat. There are three main rules in the decision tree (Fig. 1); Rules 1 and 2 rely on primary data from the source maps, whereas Rule 3 relies on processing map data. Output maps depicting peat pixels are produced from each rule. Rule 1 is the most rigorous, resulting in one output map of pixels representing peat on all three source maps. Pixels containing peat that do not satisfy the criteria for Rule 1 filter down and are examined in Rule 2. This rule is less rigorous and examines the combinations of any two of the three source maps and produces three output maps (PM_GSM, PM_COR, and GSM_COR). Pixels that fail to be allocated as peat by the first two rules are examined by Rule 3. This rule was devised to prevent pixels that are peat from being erroneously discarded. According to Hammond (personal communication, 2003), there are several CORINE land cover classes predominantly found on peat. The CORINE classes that were likely to be associated with peat soil were designated as a peat-associated vegetation class (PAVC). A PAVC is a class represented by a pixel that is not classed as peat in CORINE but is classed as peat on both the PM and the GSM. In total, 26 CORINE classes were associated with peatlands. Most of these covered very small areas, but six CORINE classes were found to cover a significant area of peat (>10 000 ha each). They were the CORINE land cover classes transitional woodland scrub, coniferous woodlands, natural grasslands, moors and heathland, pastures and diversity of agriculture, and natural vegetation. The PAVCs were then used as part of the third rule to identify pixels that were peat on PM or GSM and PAVC in CORINE. Likewise, the GSM contains soil associations that in some cases contain very high percentages of peat and which could be considered to be peat soil associations (PSA). The soil associations not classified as peat, but in some cases containing up to 75% peat, had not been examined during previous steps of the methodology. As a large number of pixels in the CORINE peat bogs class did not coincide with peat pixels on the GSM or the PM, if a CORINE "peat bog" pixel coincided with a PSA pixel, then it was treated as peat as opposed to being discarded as part of the third rule. Rule 3 produced three output maps (PM_PAVC, GSM_PAVC, and COR_PSA).

In total, seven output maps were produced from the first three rules of the decision tree. Each map was further evaluated against two qualifier conditions: (i) was the site a cut-away industrial peatland and therefore no longer a peat C store, and (ii) was the site on a slope of >25° where peat may not develop (Bellamy, 1986; Tallis, 1998; Holden, 2005). The PM (Hammond, 1979) was used to identify industrial peatlands and a digital terrain model (DTM; Mc Ginnity et al., 2005) was used to identify slopes that were >25°.

The decision tree was designed as a filtering system in which pixels that do not comply with Rule 1 are not discarded but are examined by the subsequent rules. If a pixel is not peat after Rule 3, however, it is discarded. The result of the process is a map derived from multisource map data by analysis, modification, or combination. As new data become available they can be readily introduced into the analysis. The seven output maps were amalgamated in ArcGIS using map algebra (ESRI, 2005; Zeiler, 1999). Map algebra is conducted using the raster calculator function in the ArcGIS Spatial Analysis Tool. This function enabled each output map to be added together, thus creating the Derived Irish Peat Map (DIPM).

Step 3: Ground Truth Data and Testing of the Decision Tree Rules

Each output map produced from the decision methodology needed to be ground tested to determine the reliability of each of the decision tree steps and thus the DIPM. In many

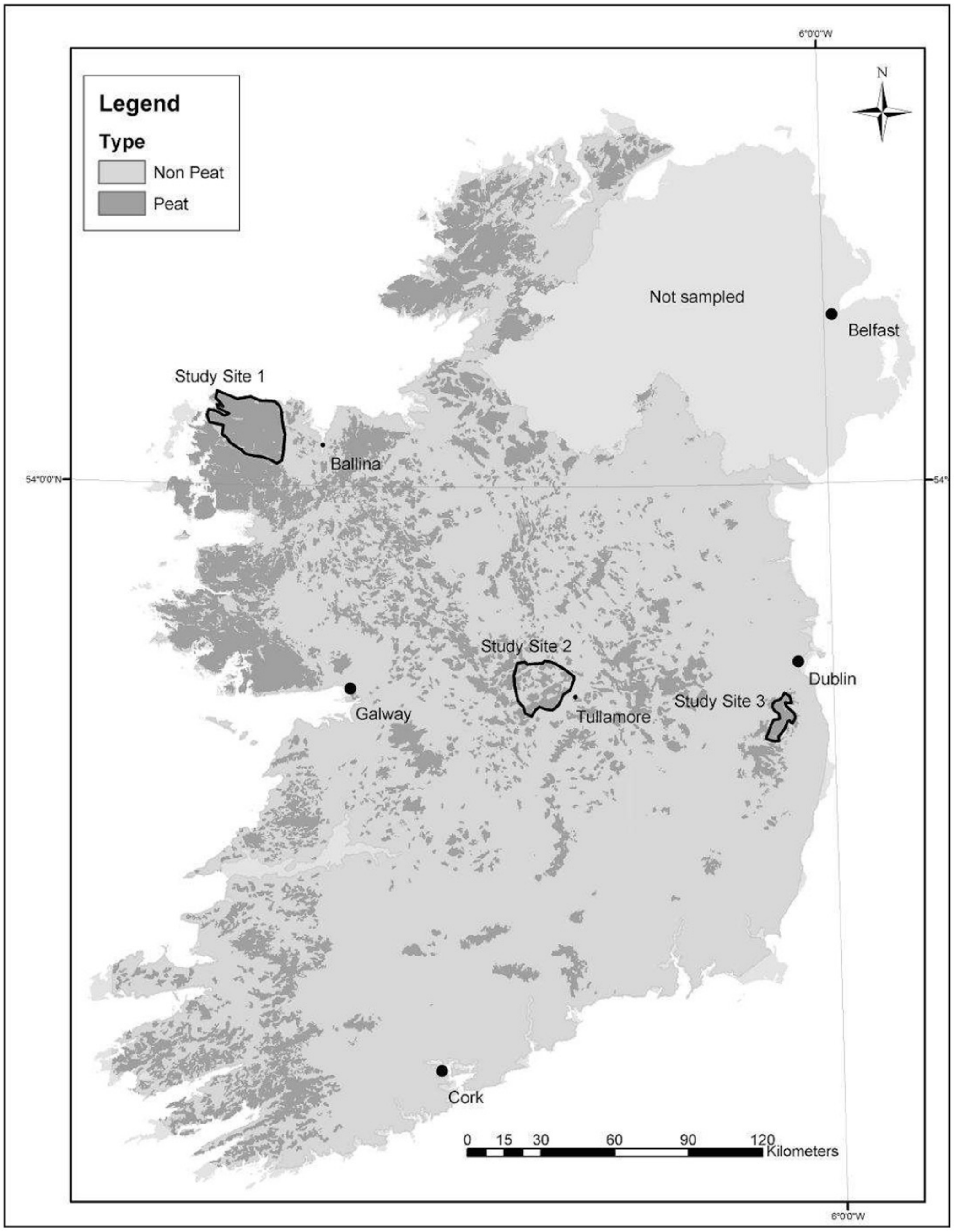

Fig. 2. Location of ground truth study sites.

cases, output maps covered the same area. To test each map, it was necessary to isolate the output maps from each other. This process was completed using the raster calculator to subtract the overlying maps from one another. This isolated each output map, enabling ground testing; thus pixels allocated by Rule 1 were not evaluated as part of the testing of Rules 2 and 3. Each of the seven output maps was individually tested using field data. The field testing was based on determining the probability that a peat pixel on the derived map is peat on the ground. The criterion used for verification of the map was that peat of at least 300 mm in depth (Lindsay and Immirzi, 1996; Sippola and Yli-Halla, 1999; Charman, 2002; Tomlinson, 2005) should be the predominant soil in the area represented by a sample pixel.

Field testing was performed in three selected areas along an east–west gradient from County Mayo in the west of Ireland (Study Site 1) through County Offaly (Study Site 2) to the Wicklow Mountains in the east (Study Site 3) (Fig. 2). The areas were selected to be representative of LLA blanket bogs, RB, and HLM blanket bogs, respectively. One hundred sample points were allocated to each of the three sites. Due to the relative inaccessibility of many peatlands, a sampling strategy involving access routes was developed. Within each study site, a digital road map (including roads, forest tracks, and walking tracks) was created in ArcGIS (Ordnance Survey Ireland, 1995). The roads were buffered to 300 m, creating a 600-m-wide buffer zone. This buffer zone was then used to delineate the area to be randomly sampled for each of the seven

Table 1. Level of agreement between ground truthing and the geographic information system rules-derived maps.

Rule no.	Name	Total sampled	Yes	No	Agreement
					%
1	3maps	73	66	7	90
2	PM_GSM	37	23	14	62
2	PM_COR	48	38	10	79
2	GSM_COR	20	11	9	55
3	PM_PAVC	36	13	23	36
3	GSM_PAVC	17	3	14	18
3	COR_PSA	45	28	17	62
	Indpeat	24	19	5	79
Total (Derived Irish Peat Map)		300	201	99	67

output maps. Within the buffered area, each output map was ranked in terms of the area that it covered, and the allocation of sampling points was area weighted. A number of industrial peatland (Indpeat) sites were also sampled (Table 1) to aid in testing the DIPM and original map sources.

A Garmin GPSMAP 76 hand-held global positioning system (GPS) receiver (Garmin International, Olathe, KS) was used in the field to determine the location of each sample area. The accuracy of the GPS ranged from 8 to 16 m, which was well within the pixel resolution of the map data. At each sample point several attributes were recorded, including peat depth, vegetation type, land use, anthropogenic influence, and overall disturbance.

Step 4: Peatland Classification

The output maps and the DIPM were produced as binary maps: peat and nonpeat. A map legend of HLM blanket bog, LLA blanket bog, and RB was developed using precipitation and elevation data. The precipitation data came from Fitzgerald and Forrestal's (1996) monthly averages for a 30-yr period from 1961 to 1990. These 30-yr monthly averages were summed to give a 30-yr annual average for each of the 600 rainfall stations in Ireland (Keane, 2001). These data were interpolated in ArcMap to give national coverage (ESRI, 2003). The elevation data were extracted from the Environmental Protection Agency of Ireland's DTM (McGinnity et al., 2005).

Precipitation provides an independent classifying property to distinguish RB from HLM and LLA blanket bog (Hammond, 1979), and elevation permits classification of LLA and HLM blanket bogs. A preliminary study using a random-point generator (Beyer, 2004) created 157 random points in peatland areas nationwide. While testing these points, it was noted that there was a lot of misclassification along the west coast and eastern Galway and Mayo, where LLA was classed as RB. To combat this, the random-point generator (Beyer, 2004) was used to create a total of 675 random points. These points were distributed nationwide but were weighted to peatland areas in the west that were misclassified in the preliminary study. Each point recorded elevation and precipitation data. Discriminant analysis was used on the 675 points to isolate blanket bogs (HLM and LLA) from raised bogs. In the database, Points 1 to 285 were classified as blanket bog, 286 to 517 were classified as a mix of raised bog and blanket bog, and 518 to 675 were classed as raised bog. The middle mixed class was extracted and subjected to further analysis using binary logistic regression in Minitab (Minitab, 2003). Based on the variables of elevation and precipitation, a formula was derived. The raster calculator in ArcMap was used to apply the formula to the elevation and precipitation data, resulting in the classification of ambiguous peatland areas in Tipperary, Galway, and Mayo.

RESULTS AND DISCUSSION

Source Data and Preprocessing

The source data used for this study were the best available at the time, but each data source was imperfect. When compiled, the PM used even older sources of unpublished information, maps, and field surveys, but was not exhaustively surveyed and had different levels of detail from the various county data sets available at the time. Furthermore, legend errors were detected during processing; these were corrected where possible during analysis. CORINE had several errors associated with the classification of land-cover types and it is known that several CORINE categories, particularly peat bogs, natural grasslands, and moors and heathland were difficult to distinguish from one another (O'Sullivan, 1994). When the GSM was compiled, only 44% of the country had been mapped in suitable detail (Coulter et al., 1998), therefore 56% of the country is based on estimation. Several counties that contain substantial tracts of peatland were not fully surveyed, including Kerry, Wicklow, Galway, Roscommon, Longford, Mayo, and parts of Donegal. Although the GSM was extensively georeferenced with >60 tic points, errors were still present at the end of this process. Cost–benefit analysis indicated that further geoprocessing was not warranted. A small number of pixels might have been discarded by the decision tree due to georeferencing errors but the area these might represent is very small. At the time this study was conducted, new digital soil maps and new CORINE maps were being produced for all counties of Ireland but these were not available for use.

Decision Rules and the Derived Irish Peat Map

The rule output maps produced by this methodology are only as good as the input maps and all the maps had faults of one kind or another. In general, with each additional rule in the decision process, the reliability of the prediction of a pixel actually being peat decreased (Table 1). Two of the output maps produced from Rule 3, the PM_PAVC and GSM_PAVC, were not included in the compilation of the DIPM because they were not reliable enough (36 and 18% ground truth agreement, respectively). The COR_PSA, the third output map produced from Rule 3, was an exception to this general trend with a reliability of 62%. The reliability of the remaining four output maps produced from Rules 1 and 2 extended from 55 to 90% (Table 1) and these were included in the DIPM (Fig. 3). There was an overall reliability of 75% for the DIPM after exclusion of industrial peatlands and sites with steep slopes. This compares with the reliability of CORINE at 65%, the GSM at 50%, and the PM at 58%, estimated using the same field data. The DIPM is more reliable than the other available data sources at the time this study was conducted so the decision process has improved the estimate of peatland spa-

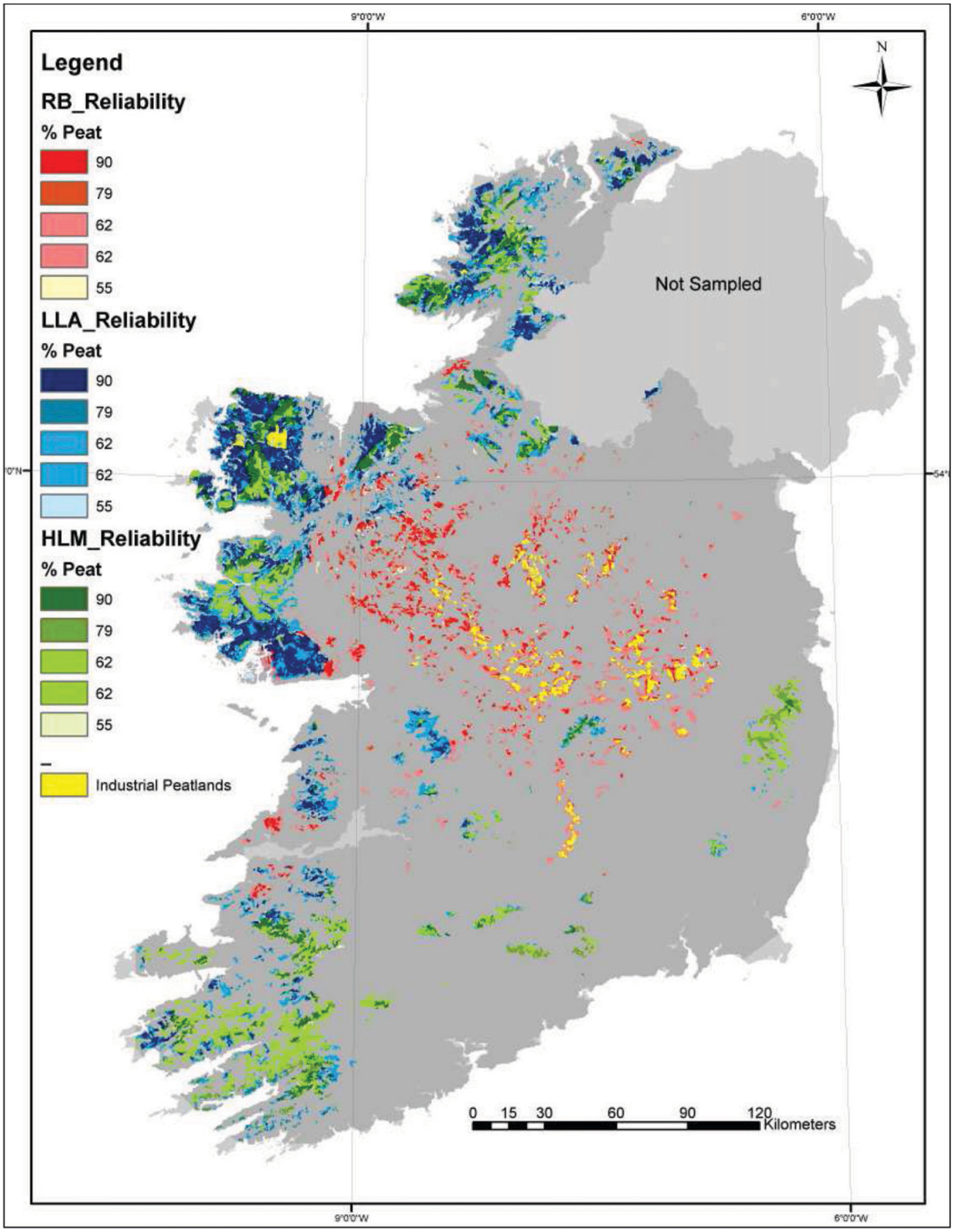

Fig. 3. The Derived Irish Peatland Map combined with the reliability map.

tial extent in Ireland. The DIPM legend (Fig. 3) indicates the spatial extent of peatlands, the type of peatland in three classes (RB, HLM, and LLA) and the probability of the presence of peat in each pixel.

Analysis of the DIPM indicated that peatland covers about 0.95 Mha or 13.8% of the land area of Ireland. This compares with 17% estimated by the PM, 16.7% estimated by the GSM, and 13.2% estimated by CORINE. The PM and GSM estimates include the areas of industrial peatlands that are excluded from the DIPM map. Also, the PM, CORINE, and GSM all include peatland areas where the slopes are >25°; therefore, it is reasonable to expect the DIPM to indicate a lesser extent of peatlands than some of the source data. The spatial errors found in the source maps will be present to some extent in the DIPM but, due to the rule approach requiring at least two pieces of evidence for a pixel to be considered peat, should be minimized. The propagation of source map error to the output maps is responsible for some of the differences between the DIPM and ground truth data. The much lower reliability in the original source maps relative to the DIPM suggests that the approach taken has been successful in creating a value-added product.

Peat Classification

The discriminant analysis and binary logistic regression used to classify the peatland map into three categories (HLM, LLA, and RB) was acceptable for most of the country. There are a small number of errors in a number of counties along the western seaboard where LLA has been misclassified as RB. The misclassification may reflect the lack of resolution in the spatial interpolation of the rainfall data used for discrimination. The spatial interpolation of rainfall data along the west coast was not good in places. This may be due to the physical landscape and spatial distribution of rainfall stations, resulting in rainfall values being interpolated across larger areas than elsewhere in the country. According to Keane (2001), this could lead to problems because rainfall accumulations between stations can vary considerably across short distances.

Peatland Disturbance

According to the field survey data, 204 of the 301 sites sampled were peat; out of these, 148, or 74%, were disturbed to some degree. A high number, 71%, of the disturbed sites had evidence of anthropogenic influences including forestry, industrial and domestic cutting (mainly historical), and grazing in HLM and LLA blanket bogs and in raised bogs. This compares with somewhat higher values reported by the Irish Peatland Conservation Council of around 82 and 92% disturbance for blanket and raised bogs, respectively (Irish Peatland Conservation Council, 1996).

CONCLUSIONS

The rule-based decision tree methodology allowed a value-added soil map product to be created from a number of data sources, all of which were to some degree imperfect. Ground truth data indicated that the DIPM was more reliable than any of the individual source data maps used in its development. The hierarchical rules, and particularly in this case, those built on identifying PAVCs and PSAs, permitted extraction of soil information from modern land cover maps by combination with older pedological-type maps. As a methodology framework, the approach to data analysis presented here could be applied to any similar digital data sets to address similar types of survey problems. Furthermore, the flexibility of the method means that new output maps can be readily created as new map data sets become available.

ACKNOWLEDGMENTS

We would like to thank the Environmental Protection Agency of Ireland for providing funding for this project under ERTDI (National Development Plan 2000–2006). We would also like to thank Dr. Robert Hammond for his help in regard to the Peatland Map of Ireland and Dr. Brian Coulter and Edward McDonald of Teagasc for providing a digital version of the Peatland Map of Ireland. Finally, we would like to thank Dr. Sean Morrish for his assistance with technical GIS issues and Dr. Lena Dahlmann for her general assistance.

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