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Mapping artificial drains in peatlands—A national-scale assessment of Irish raised bogs using sub-meter aerial imagery and deep learning methods

Wahaj Habib[1], Rémi Cresson[2], Kevin McGuinness[3] & John Connolly[1]

[1]Discipline of Geography, School of Natural Sciences, Trinity College Dublin, Dublin, Ireland
[2]French National Research Institute for Agriculture, Food and the Environment, Montpellier, France
[3]School of Electronic Engineering, Dublin City University, Dublin, Ireland

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Correspondence
Wahaj Habib, Discipline of Geography, School of Natural Sciences, Trinity College Dublin, Dublin, Ireland. E-mail: habibw@tcd.ie

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Abstract

Peatlands, constituting over half of terrestrial wetland ecosystems across the globe, hold critical ecological significance and are large stores of carbon (C). Irish oceanic raised bogs are a rare peatland ecosystem offering numerous ecosystem services, including C storage, biodiversity support and water regulation. However, they have been degraded over the centuries due to artificial drainage, followed by peat extraction, afforestation and agriculture. This has an overall negative impact on the functioning of peatlands, shifting them from a moderate C sink to a large C source. Recognizing the importance of these ecosystems, efforts are underway for conservation (rewetting and rehabilitation), while accurately accounting for C stock and greenhouse gas (GHG) emissions. However, the implementation of these efforts requires accurate identification and mapping of artificial drainage ditches. This study utilized very high-resolution (25 cm) aerial imagery, and a deep learning (U-Net) approach to map the visible artificial drainage (unobstructed by vegetation or infill) in raised bogs at a national scale. The results show that artificial drainage is widespread, with ~20 000 km of drains mapped. The overall accuracy of the model was 80% on an independent testing dataset. The data were also used to derive the $\text{Frac}_{\text{ditch}}$ which was 0.03 (fraction of artificial drainage on industrial peat extraction sites). This is lower than IPCC Tier 1 $\text{Frac}_{\text{ditch}}$ and can aid in IPCC Tier 2 reporting for Ireland. This is the first study to map drains with diverse sizes and patterns on Irish-raised bogs using optical aerial imagery and deep learning methods. The map will serve as an important baseline dataset for evaluating the artificial drainage ditch conditions. It will prove useful for sustainable management, conservation and refined estimations of GHG emissions. The model's capacity for generalization implies its potential in mapping artificial drains in peatlands at a regional and global scale, thereby enhancing the comprehension of the global effects of artificial drainage ditches on peatlands.

Introduction

Peatlands account for 50%–70% of terrestrial wetland ecosystems across the globe (Joosten & Clarke, 2002; Šimanauskienė et al., 2019) and are characterized by the accumulation of organic material (peat) in waterlogged conditions (Charman, 2002; Evans et al., 2021). Peatlands are increasingly being recognized as important ecosystems due to the provision of many services, including carbon (C) storage, biodiversity support and water regulation (Flood et al., 2021; Kimmel & Mander, 2010; Minasny et al., 2023; Page & Baird, 2016). However, increased anthropogenic pressure initiated through artificial drainage and subsequent extensive land use practices, such as industrial/domestic peat extraction, agriculture, afforestation and infrastructure development (roads), has led to significant degradation of these ecosystems and their Nature's Contributions to People (NCP; Chapman et al., 2003; Joosten, 2017; UNEP, 2022). Globally, degraded peatlands contribute significantly to current anthropogenic greenhouse gas (GHG) emissions, accounting for 4%–5% of the total global human-induced emissions (Huang et al., 2021; Strack et al., 2022).

Irish-raised bogs are particularly important among the EU's peatlands, as they comprise more than 50% of the rare oceanic-raised bogs in the region (Bullock et al., 2012). They are one of the key components of Ireland's natural capital (Farrell et al., 2022) and account for a substantial amount of Soil Organic Carbon (SOC) stock of the country (Renou-Wilson et al., 2011; Tomlinson, 2005). However, they have undergone widespread drainage, land use change and degradation (Fluet-Chouinard et al., 2023; Habib & Connolly, 2023). Hydrology plays a crucial role in the functioning and preservation of raised bogs, significantly influencing vegetation growth and peat formation and maintaining a delicate balance between water, vegetation and peat (Ivanov, 1981; Joosten, 2017; Regan et al., 2019). The development of artificial drainage to facilitate land use change leads to lowering of the water table and results in compaction, subsidence and oxidation (Mackin et al., 2015). These artificial drains also function as conduits for dissolved organic carbon, particulate organic carbon and CH_4, shifting these ecosystems from C sinks to persistent C sources (Peacock, Audet, Bastviken, Cook, et al., 2021; Regan et al., 2019). Peacock, Audet, Bastviken, Futter, et al. (2021) reported that drainage ditches and canals account for 1% of the global anthropogenic CH_4 emissions and it can be much higher for high-density drained areas. Artificial drainage also shifts peatlands from water purifiers to potential sources of water pollution (Liu et al., 2023). Yet, much like European peatlands, centuries of artificial drainage have modified the hydrology of Irish-raised bogs, leading to adverse effects on the entire ecosystem (Pschenyckyj et al., 2023; Tuohy et al., 2023). The past century has seen the widespread intensification of artificial drainage for large-scale industrial peat extraction activities, primarily carried out by Bord na Móna (BnM), a semi-state peat harvesting company (Common, 1970; Connolly & Holden, 2017). These ditches are regularly spaced at 15–30 m intervals (Wilson et al., 2015). The majority of BnM landholdings are situated within raised bogs, and a substantial amount of these lands underwent drainage and/or peat extraction (Connolly & Holden, 2011; Habib & Connolly, 2023). These activities ceased in 2020 (BnM, 2021); however, several small to medium-scale private industrial peat extraction companies continue to extract peat (Malone & O'Connell, 2009).

Several EU regulations and directives mandate the conservation and protection of these rare ecosystems. For instance, the EU Habitat Directive (92/43/EEC) and Water Framework Directive (2000/60/EC) stress the importance of conservation and enhancing water quality. Similarly, the EU Biodiversity Strategy for 2030 and the LIFE program call for the preservation and restoration of these unique habitats. Furthermore, under the EU Monitoring, Reporting, and Verification Regulation (525/2013) and EU Climate Change Framework 2030, Ireland, like other EU member states, is required to report GHG emissions and removals from Land Use, Land Use Change, and Forestry activities.

Ireland reports emissions and removals from both managed/exploited (industrial) and unmanaged peatlands for its National Inventory Report (Duffy et al., 2022). Unmanaged peatlands (all peatlands excluding exploited) are assumed to be rewet within 5 years of any anthropogenic impact and soil carbon loss also ceases in that time (Duffy et al., 2022). In exploited peatland areas, dominated by BnM, GHG emissions are recorded (Duffy et al., 2022). Currently, these emissions from artificial drainage ditches are accounted for using Tier 1 (T1) reporting, that is, a default value is given for the "fraction of the total area of drained organic soil which is occupied by ditches" or $Frac_{ditch}$. This is derived from the "mean of all data within each land use class" from several studies (Hiraishi et al., 2014). Most of these studies were based in continental Europe, Russia and Canada, with only two studies in the UK and none from Ireland. However, for Tier 2 (T1) and Tier 3 (T3), reporting countries are encouraged to develop country specific metrics. These data can include information on the spatial extent of artificial drainage ($Frac_{ditch}$), as well as characteristics including plants or algal growth within ditches and ditch maintenance activities (Hiraishi et al., 2014). However, spatial data for T2 and T3 reporting are currently not available for raised bogs in Ireland. Spatially explicit data on artificial drainage is also useful for the implementation of conservation activities (e.g., drain blocking to facilitate rewetting). Both Connolly and Holden (2017) and Robb et al. (2023) note that mapping artificial drains is difficult and expensive with traditional ground surveys. One reason is the extensive and diverse characteristics of artificial drainage ditches, including drainage density, intensity and morphology which differ from region to region (Burke, 1961; Peacock et al., 2021). This can be observed in Ireland, between industrial peat extraction areas (cutaway), and domestic peat extraction areas (cutover), that is, regular versus irregular patterns and sizes (Connolly & Holden, 2011). However, these drains can be identified through visual interpretation of very high-resolution aerial imagery, they can therefore be mapped using remote sensing techniques (Connolly & Holden, 2017).

Advanced very high-resolution optical remote sensing data, coupled with semi-automated mapping techniques, such as Object-Based Image Analysis (OBIA) and, more recently, automated deep learning based mapping techniques, have demonstrated the ability to map these drainage patterns efficiently (Connolly & Holden, 2017; Dadap et al., 2021; Robb et al., 2023). Connolly and Holden (2017) used OBIA techniques to map regular patterned drains on Irish blanket bogs using very high-resolution Geoeye-1 satellite imagery. However, OBIA requires extensive manual intervention which poses limitations for national-scale mapping. Recent developments in automated mapping, such as deep learning applied to semantic segmentation have shown significant promise in effectively mapping artificial drainage ditches, for example, in tropical peatlands (Dadap et al., 2021). These tropical drainage ditches, commonly referred to as "canals," exhibit larger dimensions compared to those found in Ireland and the UK. They also have regular patterns and were successfully mapped using high-resolution PlanetScope satellite imagery (3 m) and deep learning applied to semantic segmentation methods (Dadap et al., 2021). Additionally, highland blanket bogs in the UK, where drainage ditches are of smaller size and depict irregular patterns have also been mapped using deep learning applied to feature/object extraction (Robb et al., 2023). Artificial drainage network that has a diverse range of patterns and orientations, as well as regular and irregular shapes and sizes presents a considerable challenge for mapping using a single deep learning model.

This research addresses the challenge of accurately mapping an extensive artificial drainage network in raised bogs on a national scale. Only the visible drainage network was mapped, that is, unobstructed by vegetation canopy or infill. The drainage network was mapped across multiple land use categories, including cutaway, cutover and remnant peatlands using very high-resolution optical aerial imagery and deep learning methods. A U-Net-based (Ronneberger et al., 2015) convolutional neural network (CNN) was used for the automated pixel-wise classification of drains with a spatial resolution of 0.25 m per pixel over an extensive area of 523 000 ha. A national-scale artificial drainage map of Irish-raised bogs was created. This accurate spatial quantification and mapping may be useful for implementing sustainable management practices as well as an accurate accounting of emissions from these ecosystems.

Materials and Methods

Study area

The study area constitute of raised bogs in Ireland, delineated by the Derived Irish Peat Map version 2 (DIPMv2; Connolly & Holden, 2009). These bogs are spread across the midland region of Ireland, covering about 523 000 ha, constituting ~35% of the total peatland area and 8% of the land surface area of Ireland (Connolly & Holden, 2009; Feehan & O'Donovan, 1996). They are characterized by low-lying vegetation cover that mainly consists of mosses (*Sphagnum* species), sedges and heather. As of 2017, it is estimated that less than 1% of raised bogs in Ireland are actively forming peat (NPWS, 2017).

Drainage types (land use)

The drainage assessment was primarily focused on three land use types: cutaway, cutover and remnant peatland (Table 1). Different drainage patterns are associated with each land use. In cutaway areas, artificial drainage tends to exhibit more regular structure and spacing between drains, for example, 15–30 m on BnM industrial peat extraction sites. In cutover areas where traditional manual digging of drains may have taken place in the past, irregular shapes and sizes can be seen. Remnant peatlands might exhibit both regular and irregular patterned drains depending on the peat extraction activities in the margins, that is, domestic or industrial. It also includes "high bog" areas, which are bog domes that are not directly cut and are surrounded by peat extraction activities (NPWS, 2017). Overall, drainage orientation and spacing vary significantly between land use, and drainage conditions may

Table 1. Description of land use classes, with area for each class in hectares (ha) (Habib et al., 2024).

Land use class	Description	Area (ha)
Cutaway	Land that has been subjected to peat extraction, with the peat removed and the land left bare, with a thin layer of soil, managed by BnM and other private companies with large-scale industrial/mechanized peat extraction	54 302
Cutover	Land that has been subjected to peat extraction peat removed and the land left bare, hand-cut and small-scale mechanized domestic peat extraction	64 699
Remnant/ Revegetated Peatland	Land that has a high percentage of peat including near natural and high bog areas. It is characterized by the presence of *Sphagnum* mosses and other bog flora, not directly affected by human intervention. Also, revegetated areas post extraction activities	73 795

change over time due to factors like drain collapse, vegetation cover and infill.

Aerial imagery

The spatial extent of artificial drainage on raised bogs was assessed using an extensive dataset of 5111 aerial image tiles providing wall-to-wall coverage for raised bogs, as defined by the DIPMv2 (including an additional 50 m buffer to incorporate peripheral areas). The images were produced by BlueSky International Limited using a manned survey aircraft with gyro-stabilized mounted sensors, that is, Vexcel UltraCam MK3. The images were acquired between 2015 and 2021, with each image comprising four bands, that is, Blue, Green, Red and NIR (R, G, B and NIR), with a size of $\sim 2 \times 2$ km and spatial resolution of 0.25 m. Pixel encoding was unsigned byte (8 bits, unsigned i.e., values ranging from 0 to 255) and no pre-processing was implemented. The total volume of the images was 1.3 terabytes. To efficiently manage, store and access the images, a "*mosaic dataset*" was created using ArcGIS Pro version 3.1 desktop software. The very high spatial resolution (0.25 m) and limited to no cloud cover are the two salient features of this dataset for mapping narrow (<0.50 m width) drainage features in otherwise persistent cloud-obscured conditions in Ireland.

Training, testing and validation sample data

To the best of our knowledge, there is no publicly available dataset with accurate georeferencing depicting the spatial extent of artificial drainage in Irish-raised bogs which could be used for training the model. Therefore, training data were developed for this study using the heads-up digitization method by employing the visual interpretation technique on very high-resolution aerial imagery. It was collected by digitizing drains with a diverse set of characteristics (size and orientation) covering ~ 400 km at two bog sites (Fig. 1B and C–outlined by green box). The drainage lines were digitized at the center of each drain and were extended by an additional 0.25 m using the "buffer" tool within ArcGIS Pro v3.1. This step transformed the lines into polygons and generated well-annotated data suitable for training a deep learning model. Moreover, by incorporating the buffer, the resulting masks contained more pixels, providing efficient bank-to-bank coverage of the ditches and contributing to improved accuracy. The training images and masks (created from digitized drains) were cropped into patches of 64×64 pixels. The cropping process was implemented to enhance computational efficiency, facilitate optimal model training and improve the model's ability to discern patterns within smaller, localized features in the images.

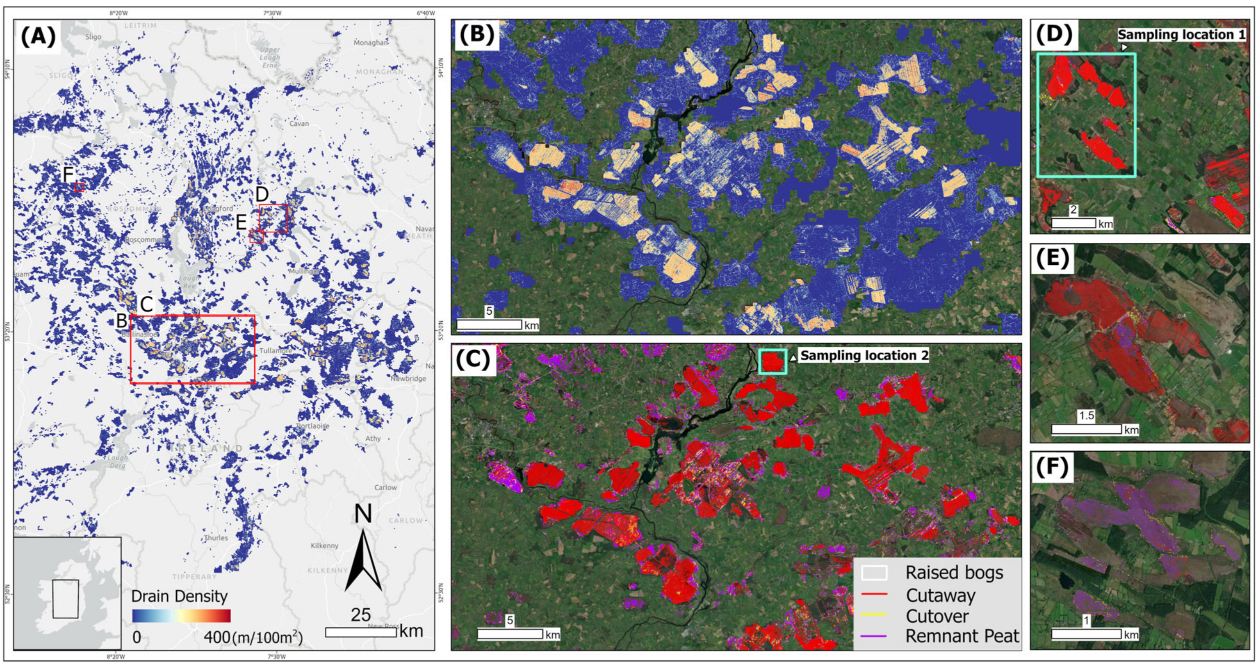

Figure 1. (A) Drainage density map (m/100 m^2), (B and C) BnM (Bord na Mona)-based industrial peat extraction areas, (B) shows the drainage density and (C) shows the individual ditches (D and C) sample locations 1 and 2 (E) non-BnM-based industrial peat extraction activities, (F) remnant peatland (high bog) area with extensive drainage.

The final training dataset consisted of 22 748 (64 × 64 pixels) four-band images. The sampling dataset was divided into training, validation and testing subsets using a 70-15-15 split. The training subset, comprising 70% (15 924 image patches) of the data, allowed the model to learn patterns and adjust parameters. Meanwhile, the validation subset which comprised 15% (3412 image patches), served as an independent benchmark to assess the model's performance on new data and choose the best model across training iterations. Finally, the model was tested on 15% of the completely independent testing data (3412 image patches) to evaluate the trained model. The training, validation and testing data consisted of samples for all three types of land use (Table 1), and both uniform (industrial) and nonuniform (domestic) drainage were considered.

Classification of imagery

Convolutional neural network (CNN) model

Mapping of the spatial extent of artificial drainage using aerial imagery was accomplished using a U-Net model (Ronneberger et al., 2015). The model consisted of approximately 34 million parameters. This was used to predict the extent of artificial drainage for each pixel in the input image. For this task, a four-band image (R, G, B and NIR) with dimensions of 64 × 64 pixels and a spatial resolution of 0.25 m was employed as input. The training sample data underwent data augmentation, such as random brightness, contrast, hue and random horizontal and vertical flips, before being fed to the model. For optimization, the Adam optimizer was used, with a learning rate of 0.0001. A custom loss function consisting of the sum of the Binary Cross-Entropy Equation (1), and the Dice loss in Equation (2) is used in Equation (3) to encourage accurate segmentation and effective boundary delineation.

$$\text{BCE loss} = -\frac{1}{N}\sum_{i=1}^{N}\left(y_{\text{true}}.\log\left(y_{\text{pred}}\right) + \left(1-y_{\text{true}}\right)\cdot\log\left(1-y_{\text{pred}}\right)\right) \tag{1}$$

$$\text{Dice loss} = \left(1-\frac{2.\sum\left(y_{\text{true}}\cdot y_{\text{pred}}\right)}{\sum y_{\text{true}} + y_{\text{pred}} + \epsilon}\right) \tag{2}$$

$$\text{BCE Dice loss} = \text{BCE loss} + \text{Dice loss} \tag{3}$$

where y_{true} is the ground truth, y_{pred} are predicted values (probability scores), is a small constant to prevent division by zero and N is the total number of elements (pixels) in the tensors.

The entire network was trained for 600 epochs, with a batch size of 32 images over the training dataset. The training was concluded when loss values showed no further decrease over the validation dataset, and the model with the minimum loss across epochs was retained for inference. The model training was completed in less than a day using an NVIDIA RTX 2080 Graphics Processing Unit (GPU) equipped with 12 GB of memory.

The model produced a binary output with values of either 0 or 1, where a value of 1 indicated the presence of a drainage pixel. The model was implemented using the Keras framework in R language with the RStudio interface and TensorFlow version 2.8 (Allaire & Chollet, 2019).

Model assessment

Previous studies that mapped the drainage network on peatlands have noted the challenges associated with the accuracy assessment of drainage lines using traditional methods (Connolly & Holden, 2017; Dadap et al., 2021; Robb et al., 2023). Assessing the accuracy of these linear features is challenging, primarily because of the presence of a high proportion of true non-drainage pixels. The testing dataset was used to assess the model's accuracy. The accuracy was assessed using the F_1 score in Equation (6), which is the harmonic mean of the precision in Equation (4), and recall Equation (5), which is a popular combination that symmetrically represents both precision and recall in one metric. Precision is a measure that represents the proportion of true positive results (correctly predicted positive results) among the total predicted positives. The inverse of the precision is the error of commission. Recall, also known as sensitivity or true positive rate, represents the proportion of true positive results (correctly predicted positives) among the actual positives. The inverse of recall is the error of omission.

$$\text{precsion} = \frac{\text{tp}}{\text{tp} + \text{fp}} \tag{4}$$

$$\text{recall} = \frac{\text{tp}}{\text{tp} + \text{fn}} \tag{5}$$

$$F_1 = 2\cdot\frac{\text{precision}\cdot\text{recall}}{\text{precsion} + \text{recall}} \tag{6}$$

where tp are true positives, fp false positives and fn are false negatives.

Inference

At the inference stage, the images with the original tile size, that is, 2 × 2 km were used. For faster processing, inference was performed on bigger patch sizes than training, that is, 512 × 512 pixels with a 64 pixels (16 m) overlap to mitigate the border artifacts (Ronneberger et al., 2015). Inference was conducted on each sub-patch of each image patch, excluding the margins of the overlapped pixels. The final output patches were then mosaicked into a single binary image representing the drainage map. The processing time for the imagery covering raised bogs at the national scale (523 000 ha) was approximately 1 month using a single RTX 2080 GPU.

Density mapping

The classification results were initially obtained in a raster format, representing drains and non-drains within the study area at the pixel level. To facilitate geospatial analysis, such as length calculation and density mapping, several post-processing steps were performed in ArcGIS Pro. Given the variable drain width, that is, ranging from one to three pixels, the ‘thin’ tool was used to extract the central pixels of the drain networks. The transition from raster to vector was completed using the ‘raster to polyline’ tool, resulting in drain-vector lines. These lines were further optimized by applying the ‘smooth line’ tool using Polynomial Approximation and Exponential Kernel with a smoothing tolerance of 0.75 m to achieve a more refined representation. Finally, the derivation of drain density maps was accomplished using the ‘line density’ tool with a cell size of 10 m to match the land use map. This process delivers a comprehensive visualization of the peatland drain network distribution in the form of a density map of all raised bogs in Ireland (Fig. 1A and B). Furthermore, it allows for the quantitative assessment of drains in the form of the total length of drains. This was further segregated for each land use based on high-resolution peatlands land use map (Habib et al., 2024).

Updating the fraction of drainage ditches

The 2013 wetland supplement, an extension of the 2006 IPCC guidelines, outlines a method to estimate C and GHG emissions and removals from drained inland organic soils (Hiraishi et al., 2014). An essential element of this calculation is $Frac_{ditch}$ Equation (7). According to these guidelines, the estimation of emissions is based on multiple levels of detail. T1 relies on the default values of $Frac_{ditch}$ available in the wetland supplement. By contrast, T2 and T3 are based on country-specific values.

$$Frac_{ditch} = \frac{\text{area covered by drianage ditches(ha)}}{\text{area covered by land use class impacted by drainage ditches(ha)}} \quad (7)$$

where the area covered by drains is equal to the width of the ditches multiplied by their total length (Hiraishi et al., 2014).

Results

Over 523 000 ha of raised bogs were assessed using very high-resolution aerial imagery and a deep learning applied to a semantic segmentation modelling approach. The total surface area covered by the drainage on raised bogs was approximately 2000 ha. This was calculated from pixels identified as drains. The total length of the detected and mapped drains was approximately 20 000 km. The drains were further segregated by land use categories based on the raised bogs land use map developed using Sentinel-2 (Habib et al., 2024). Cutaway bogs account for the majority of the mapped drains, that is, 16 000 km (Fig. 1C). The cutover drains account for ~1600 km and are mostly located at the periphery of the cutaway sites (Fig. 1D–F). The rest of the drains occur on remnant peatland sites, that is, ~2400 km.

The overall spatial distribution of drainage network density can be seen in Figure 1A. The density map (Fig. 1B) reveals that the drainage was more prevalent in the majority of the BnM peat extraction sites. Cutaway drains are systematically placed with the highest density of 400 m/100 m^2. The maximum drainage density for remnant peatlands (high bogs) was 250 m/100 m^2 and it was lowest for cutover bogs, that is, 200 m/100 m^2. There is also a presence of extensive drainage on non-BnM peat extraction sites. Figure 1E shows one such site, possibly owned by a private industrial peat extraction company.

To further examine the results, boundary data from BnM was used to assess the status of drainage under industrial exploitation. The results show that most of the drains mapped in this study exist on BnM-based industrial peat extraction sites, that is, approximately 14 000 km or 70% of the total drainage network identified. A relatively small proportion of remnant peatlands (high bog), and cutover drains are also present on BnM landholdings (Table 2).

Fraction of drainage ditches

The value for $Frac_{ditch}$ for BnM landholdings was calculated using Equation (7). Only the cutaway land use class

Table 2. Drainage length in kilometres (km) of detected drainage overall and BnM (Bord na Móna) landholdings.

Land Use	Overall (km)	BnM (km)
Cutaway	16 000	14 000
Remnant peatland	1600	611
Cutover	2400	514
Total	20 000	15 125

was considered because most of the drainage networks at these sites were identifiable using optical aerial imagery. This is largely due to the presence of these artificial drainage ditches in bare peat sites, unobstructed by vegetation canopy or infill, unlike cutover and remnant peatlands classes. The land use class area was 42 264 ha, sourced from Habib et al. (2024). The drainage ditch area for the same land use class was 1300 ha as calculated in this study from the total length of drainage on BnM peat extraction sites, that is, 13 000 km and an average width of 1 m (BnM, 2016). The $Frac_{ditch}$ value obtained was 0.030.

Classification accuracy

The results were assessed both qualitatively (visual inspection) and quantitatively. The qualitative assessment shows that the model can capture the details of spatial patterns in all land use types across the study area at a national scale (Fig. 1C–F). Both the regular patterns of cutaway peatlands and irregular patterns of cutover peatlands were accurately mapped. A quantitative assessment was conducted using the F_1 score in Equation (6). The testing dataset yielded an F_1 score of 0.80 (Table 3), indicating a good agreement between the drainage maps and reference data.

Discussion

This study presents the first map of an artificial drainage network across 523 000 ha of Irish-raised bogs. Over 20 000 km of small artificial drains (<1 m wide) were detected and mapped using optical aerial imagery, with an accuracy (F_1 score) of 80%. To the best of our knowledge, this is the first drainage map of temperate (European) peatlands at this scale. The U-Net-based semantic segmentation model adapted for this study identified a drain network with good accuracy on an independent testing dataset, demonstrating the ability of CNN to map artificial drainage features on peatlands (Dadap et al., 2021). Previous studies in Ireland utilizing OBIA required extensive manual interventions and were applied to a smaller study area in blanket bogs (Connolly & Holden, 2017). Whereas the deep learning applied to semantic segmentation based approach for mapping was carried out by Dadap et al. (2021) on tropical peatlands assessed larger size (>5 m wide) regular patterned drainage "canals." On the other hand, Robb et al. (2023) used deep learning applied to feature/object detection to identify irregular pattern "drain features" on highland blanket bogs and focused on a smaller area. The deep learning model employed in this study facilitated the mapping of an artificial drainage network across multiple land use categories in raised bogs at a very high resolution (submetre) on a larger scale. The diversity of land use and drain types (range of size, orientation and patterns) mapped, combined with the model's high accuracy, shows its global application for mapping artificial drains across a variety of peatland types where drains are visible in optical imagery.

Table 3. Results of accuracy assessment (Precision, recall and F_1 scores).

Metric	Value
Precision	0.76
Recall	0.85
F_1 Score	0.80

The results quantified the spatial extent and density of drains on raised bogs. This affirms the widely acknowledged drainage status of these ecosystems in Ireland (Common, 1970; Wilcock, 1979; Wilson et al., 2022). This study also addresses the knowledge gap by providing robust spatially explicit data for land use activities on peatlands in Ireland (Aitova et al., 2023; Wilson et al., 2013). Current C and GHG emission estimations from peat extraction-based artificial drainage ditches in Ireland rely on the T1 default $Frac_{ditch}$ value (0.05) available in the wetlands supplement (Duffy et al., 2022; Hiraishi et al., 2014). This is an average indicative value derived from several local-scale studies conducted on temperate and boreal peatlands. In this study, the $Frac_{ditch}$ 0.03 was obtained for cutaway raised bogs in Ireland. This is lower than the IPCC default value (0.05) currently used in the National Inventory Report (Duffy et al., 2022). This new value also allows for more "rationalized and reflective estimates" of C and GHG emissions (Tuohy et al., 2023) from cutaway bogs and can facilitate both T2 and T3 approaches for methane emission estimation (Hiraishi et al., 2014). However, the $Frac_{ditch}$ value was not calculated for the non-industrial areas because drainage in these areas could not be mapped comprehensively due to limitations of optical remote sensing data. Future work with the integration of active remote sensing data (e.g., LiDAR) with the very high-resolution aerial imagery (Carless et al., 2019; Koski et al., 2023) could provide enhanced detection of drainage ditches and refined $Frac_{ditch}$ values for both raised bogs and blanket bogs in Ireland. Furthermore, the use of LiDAR-derived high-resolution elevation data combined with optical data is also important for assessing the condition of ditches (Koski et al., 2023).

Distinct patterns of drains were identified within each of the three land use categories. The prevalence of regular patterned industrial drains, especially within BnM landholdings, stands out, whereas the presence of extensive drainage on cutover and remnant peatland sites (where detectable using optical imagery) provides valuable insights on domestic peat extraction and drainage of raised bogs. Industrial peat extraction sites (mainly BnM) accounted for the majority of high-density artificial drainage ditches, followed by remnant peatlands and cutover sites. This can be seen in the density maps (Fig. 1A and B).

Condition of drainage ditch network

Drainage maps can also be used to infer the condition of the drains (Connolly & Holden, 2017). For example, the low drainage density areas on the cutaway and cutover sites could be interpreted as overgrown or deteriorated drains. Artificial drainage ditches can also impact peatland subsidence rates, with a clear correlation between drainage density and subsistence rates, as shown in regional studies (Dadap et al., 2021). The density map produced here could be used to infer the subsidence rates of raised bogs and the overall condition of raised bogs.

Cutaway drainage

Approximately 90% of the BnM sites were drained or subjected to peat extraction activities (Habib & Connolly, 2023). These areas also have the highest density of drains at 400 m/100 m^2; however, there are also low drainage density zones on BnM landholdings (Fig. 1D). These zones may indicate areas that have been inactive in peat extraction for the past 10–20 years (NPWS, 2017). The abandonment of these areas may lead to drain structure degradation, occlusion and partial collapse (Connolly & Holden, 2017). This possibly facilitates revegetation (Fig. 2A) and infilling (Fig. 2B), making them less discernible in optical aerial imagery. Some of the sites are also going through rewetting and rehabilitation. At these locations, intervention measures such as peat dams and borrow pits can be seen in Figure 2C. Overall, the spatial extent of the drainage network and patterns was robustly measured for industrial peat extraction areas in both BnM and non-BnM landholdings. This may be attributed to the fact that the majority of these drains are located on

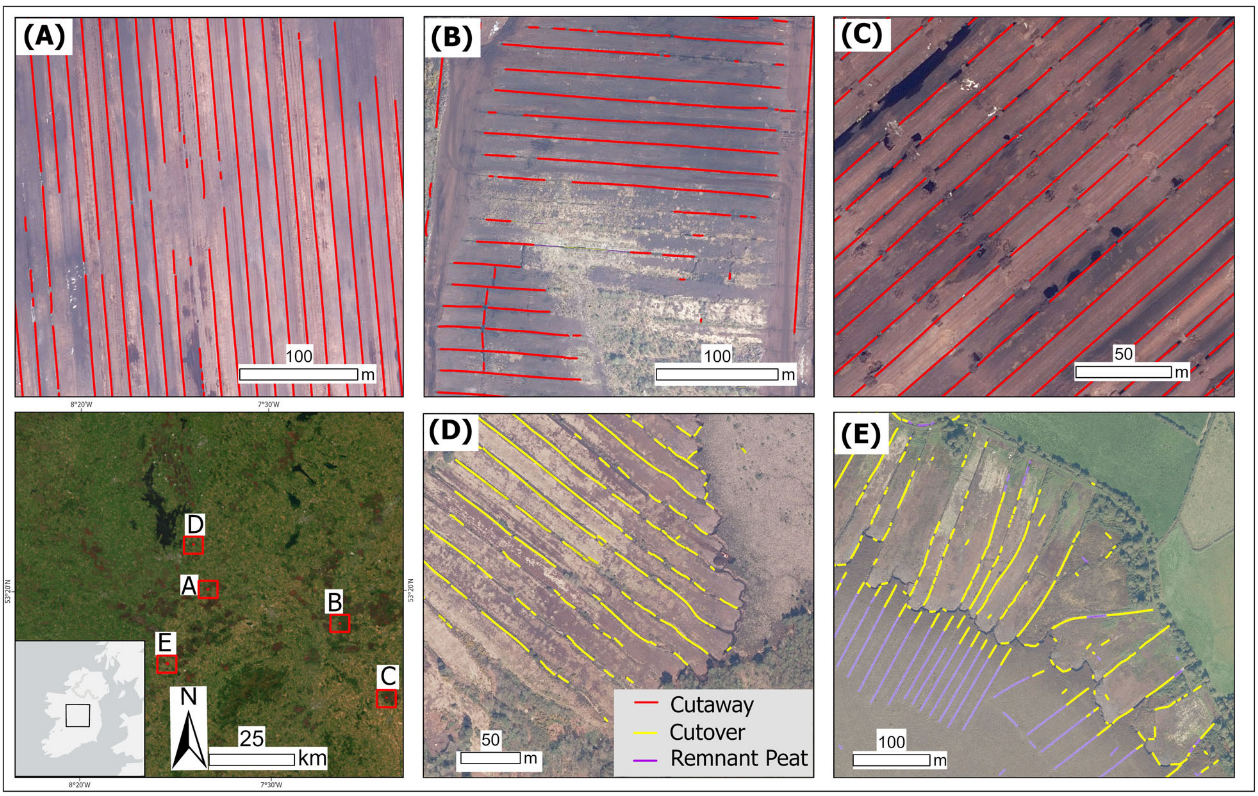

Figure 2. Different types of drainage ditch conditions on each land use. (A) Industrial peat extraction site, drainage infilled with peat. (B) revegetation of former industrial peat extraction site owned by BnM. (C) Drains blocked with peat dams (borrow pits). (D) The pattern of drainage on a cutaway site with drains in-filled and covered with vegetation (E) cutover site with remnant peatland (high bog) towards the South and partially covered with vegetation on the North.

cutaway bogs and are not obscured by vegetation canopies, infills, etc.

Cutover drainage

Cutover sites exhibit a drainage network, characterized by haphazard patterns of various sizes (length and width). Some of these drains have been in use for centuries and display a range of conditions (Fig. 2D and E). The cutover sites exhibited the lowest drainage density among the three land uses mapped in this study, yet this metric does not precisely reflect the true spatial extent of the drainage within this land use category. This is because many drains on cutover sites exhibit re-vegetation and embankment deterioration (Fig. 2E), making accurate detection and mapping challenging with optical aerial imagery. However, as Connolly and Holden (2017) observed, these broken line patterns may illustrate the drain condition. This could make these maps useful for monitoring sustainable management at these sites.

Remnant peatland drainage

Drains traversing through high bogs and surrounding bog margins effectively reduce water tables within peat, impeding the hydrological conditions essential for peat accumulation (Mackin et al., 2017). The density of the drainage network within remnant peatlands (high bog) exceeds that of cutover peatlands (250 m/100 m^2), yet it is lower than that observed in cutaway peatlands. Nevertheless, this shows that the raised bogs within this land use category are not in pristine condition (Smith & Crowley, 2020). The drainage pattern exhibits variability contingent upon proximity to peat extraction operations (both industrial and domestic), a systematic pattern observed in proximity to cutaway areas, while irregular patterns characterize areas near the cutover sites. One such site is shown in Figure 2D, a typical cutover peat extraction area. The drainage pattern here closely resembles the cutover regions towards the North (Fig. 2E).

Implications of the study

The methods used in this study are a robust and cost-effective way fo qualitative and quantitative assessment of artificial drainage ditches on raised bogs in Ireland. The methods are also fully automated and can be deployed at large scales; therefore, they could be applied to other artificially drained peatlands in Ireland (e.g. blanket bogs) across Europe and globally. It requires no manual intervention compared with the OBIA method (Connolly & Holden, 2017) and can detect a wide range of artificial drainage ditches with diverse characteristics compared with previous studies (Dadap et al., 2021; Robb et al., 2023). The output map provides valuable and much-needed spatially explicit information on the extent and fraction of drains which is useful for many stakeholders, including those restoring, managing and monitoring peatlands, as well as for accurate National Inventory Reporting.

Local-scale studies have shown the effect of drainage on ecosystem services provided by peatlands, including C storage/sequestration and water provision (Regan & Johnston, 2010). The drain map produced in this study can facilitate a large-scale assessment of the implications of drainage on raised bogs for various land use activities and GHG emissions. Without drain blocking, peatlands are prone to becoming drier and more susceptible to fires over time, leading to increased C and GHG emissions (Brown et al., 2015; Price et al., 2003). Drains are also CH_4 hotspots (Cooper et al., 2014; Peacock, Audet, Bastviken, Cook, et al., 2021); therefore, mapping the extent and condition of artificial drains may facilitate the refinement of GHG emission estimation and reporting, as well as cost-effective restoration, rehabilitation and rewetting activities.

The methodology can also be effectively used to monitor and track conservation activities (Fig. 2C). Artificial drainage ditch data will be a valuable resource for designing and implementing effective restoration and rehabilitation plans for Irish-raised bogs, leading to improved ecosystem function and enhanced carbon sequestration. Overall, as pointed out by Connolly and Holden (2017), the two main uses of the drain maps are (i) identification of C and GHG emission hotspots and (ii) identification of suitable areas for drain-blocking activities (rewetting). This work shows additional applications of the data by providing details ($Frac_{ditch}$) that are useful for both T2 and T3 reporting (Hiraishi et al., 2014), ditch maintenance activities and capturing seasonal dynamics, particularly if the study was repeated using high temporal and spatial resolution satellite remote sensing datasets. The map produced here will also provide valuable information for land use policy and conservation efforts in Ireland, leading to more informed decision-making and better outcomes for raised bog ecosystems.

Conclusion

The significance of peatlands is increasingly being recognized due to their large stores of C and GHG emissions due to degradation. Peatland degradation starts with artificial drainage ditches. However, uncertainty exists regarding the status and condition of artificial drainage ditches, and consequently, peatland ecosystems. Understanding the regional and global effects of artificial drainage ditches on peatlands is hindered by a lack of spatially explicit data. Mapping these drains accurately is time and cost-prohibitive. However, utilizing deep learning combined with very high-resolution optical aerial imagery offers a cost-effective way for national-scale mapping of drainage ditches that are unobstructed by vegetation canopy or infill. It is useful for the identification of extent, condition of drains and emission hotspots. Such maps support spatial and temporal monitoring, which is crucial for conservation efforts. Incorporating artificial drainage maps into the National Inventory reporting aligns with the IPCC reporting guidelines, enhancing reporting accuracy at the T2 and T3 levels. The deep learning method used in this study can detect visible (unobstructed by vegetation, infill, etc.) small artificial drains (~ 1 m wide) in peatlands with a high degree of accuracy. It can also detect a diverse range of drain patterns and sizes (length and width) across three different land use categories on raised bogs. The model's ability to generalize suggests its potential for mapping artificial drains in peatlands at regional and global scales. This could contribute to a better understanding of the global impact of artificial drainage ditches and facilitate sustainable management.

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Author Contributions

WH led to the preparation, creation, and presentation of the published work, specifically writing the initial draft. WH took a lead role in the development and design of the methodology. WH, JC, and KMcG conceptualized this study. JC and KMcG supervised the study. RC worked closely with WH to improve the model performance and advised on the analysis and accuracy assessment. JC and RC also contributed to the writing by reviewing and editing the manuscript.

Data Availability Statement

The data that support the findings of this study are openly available in the Open Science Framework data repository at https://doi.org/10.17605/OSF.IO/HGNQ5).

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