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Deforestation in Ireland 2000 – 2012

John L. Devaney[a, b*], John J. Redmond[c], Grace M. Cott[a, b] and John O'Halloran[a]

Abstract

Although Ireland's national forest area continues to expand, recent evidence has suggested that the gross annual rate of deforestation is also increasing. Heretofore, no spatially explicit characterisation of contemporary deforestation areas in Ireland exists. Given uncertainties associated with current deforestation estimates, investigation of new methodologies is required to inform future land-use change accounting approaches. This paper presents a summary of the DEFORMAP project, which investigated the extent and nature of deforestation in Ireland for the 2000 – 2012 period. A combination of high resolution aerial photography, satellite imagery and ancillary datasets was used to quantify forest loss in the Republic of Ireland. In total, 5,457 ha of deforested land was identified which, following accuracy assessment, was error-adjusted to 7,465 ±785 ha. The error-adjusted gross annual national deforestation rate for the period of study was 0.103%. The deforestation rate increased from the first time interval investigated (2000-2005) to the second (2005-2010), followed by a reduction during the 2010 – 2012 period. High inter-county variation in gross annual deforestation was identified, with the highest level of deforestation occurring in Co. Monaghan (0.25% yr^{-1}) and the lowest in Co. Limerick (0.02% yr^{-1}). Principal post-deforestation land-use transitions were to agricultural grassland, built-land and wetland. Patterns of post-deforestation land-use transitions varied widely between counties indicating changing regional pressures on forest land. This paper presents an important development in our understanding of contemporary land-use change in Ireland by developing the first national deforestation map. The Deforestation Map presented here will provide a valuable record of forest loss, which can be used to validate any future earth observation based deforestation monitoring approaches, such as automated radar remote sensing techniques.

Keywords: *Deforestation, Ireland, UNFCCC, National Forest Inventory, Land-use change*.

Introduction

Ireland's afforestation programme has rapidly increased forest cover from <1% at the turn of the 20th century (Mitchell 2000) to now almost 11% (Forest Service 2013). Indeed, forest policy in Ireland targets an increase of national forest cover to 18% by 2046 (Forest Service 2014). While the extent of forest cover in Ireland continues to expand, recent evidence from Ireland's National Forest Inventory (NFI) suggests that the gross annual deforestation rate may also be increasing (Forest Service 2013, Forest Service 2007).

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As a net carbon sink, Ireland's forests make a significant contribution to national greenhouse gas reduction targets (Byrne 2011). Since its establishment in 1994, the United Nations Framework Convention on Climate Change (UNFCCC) has required Annex 1 Parties to provide an annual inventory of afforestation, reforestation and deforestation areas. NFI information is a key component of deforestation reporting under the Land-Use, Land-Use Change and Forestry (LULUCF) sector of Ireland's National Inventory Report (NIR) on greenhouse gas emissions to the UNFCCC. As part of the NFI, over 1,800 permanent sample forest plots are resampled on a periodic basis and their land-use is determined by ground survey and imagery interpretation. However, for countries where deforestation is a relatively rare event, area estimates based on this methodology can be associated with high levels of uncertainty (Dymond et al. 2008). In Ireland for example, for the period 2000 – 2006, the total NFI derived national deforestation area estimate (±95% confidence intervals) was 6,000 ha ± 3,000 ha (Forest Service 2007). Other existing deforestation data, such as limited felling licence records, are subject to errors as no unlicensed or exempted deforestation activities are accounted for.

In Ireland, for NFI and other national and international deforestation reporting, the UNFCCC definition of deforestation is adopted i.e. "the direct human-induced conversion of forested land to non-forested land" (Penman et al. 2003). Hence, as long as replanting occurs within a five-year period, forest management operations such as clear-felling, do not constitute deforestation. Features that form part of forest infrastructure, such as forest roads, are considered part of forest land-use and are not deemed deforestation activities. Examples of deforestation (permanent land-use changes) include the construction of windfarm infrastructure, motorways, housing settlements on forest land, and the conversion of forest to agricultural uses.

Given the uncertainty associated with current deforestation estimates, investigation of new methodologies is required to inform future land-use change accounting approaches. Heretofore, no spatially explicit characterisation of contemporary deforestation areas in Ireland exists. To address this knowledge gap, in 2012 the DEFORMAP (Deforestation Estimation and Mapping in Ireland) project was initiated. This project set out to characterise the nature and extent of contemporary deforestation in Ireland. A combination of high resolution aerial photography, satellite imagery and ancillary datasets has been used to provide a spatially explicit map of deforestation in Ireland for the period 2000 – 2012. This paper presents a summary of the findings of the DEFORMAP project. Particular emphasis is placed on the rate of gross annual deforestation per county, land-use transitions and forest type and ownership.

Materials and methods

Using a combination of available records of deforestation in Ireland and interpretation of imagery, a national deforestation map for the 2000 – 2012 was created, hereafter termed the Deforestation Map. The process by which this map was created is outlined below and in Figure 1. Throughout, the forest definition used for UNFCCC reporting in Ireland was applied, i.e. land with a minimum area of 0.1 ha, trees >5 m in height and canopy cover ≥20% (or the potential to reach those thresholds *in situ*) (Duffy et al. 2014).

Photointerpretation

Wall-to-wall manual photointerpretation of high-resolution aerial imagery was carried out for the Republic of Ireland. Three series of orthorectified aerial photography were available: Ordnance Survey Ireland (OSI) 2000, 2005 and 2010 orthophotos at a scale of 1:40,000 and pixel size of 1 m. National scale

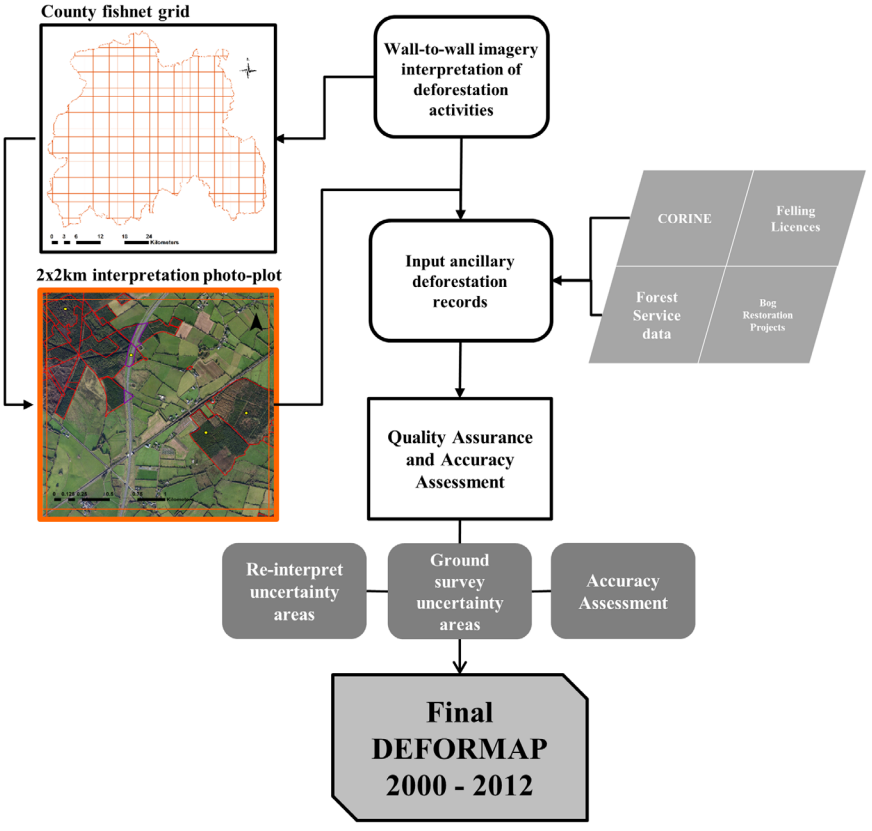

Figure 1: *Production flow chart of the Deforestation Map.*

high resolution (<1 m) aerial imagery, captured between November 2011 and May 2012, was also obtained through the Bing Maps base layer function in the geographic information system (GIS) software ArcGIS 10.2. A "fishnet" grid was used to create interpretable 2 × 2 km photointerpretation "photo-plots" (Figure 1). In total, 18,889 photo-plots were interpreted at a scale of 1:8,500. Hence, imagery for the entire land mass of the Republic of Ireland was analysed. A time-series visual assessment of geo-rectified imagery for each photo-plot was carried out to identify any deforestation events during three time intervals: 2000 – 2005, 2005 – 2010 and 2010 – 2012. A deforestation event was defined as any area where a clear land-use transition (LUT) from forest to non-forest land-use had occurred. Two existing forest vector datasets were used to aid interpretation: (1) the most recent Forest Service national forest cover map (Forestry 2012) and (2) the Irish National Survey of Native Woodland (Perrin et al. 2008) spatial dataset of native woodlands in Ireland. The spatial extent of each deforestation event was digitised and a suite of attributes was recorded including forest type, age, ownership, and land-use transition (LUT). Categories of forest type were conifer (at least 81% canopy cover of coniferous trees), broadleaf (at least 81% canopy cover of broadleaf trees), and mixed (broadleaved and conifer species, the minor category making up at least 20% of the canopy). Categories of forest age were <20 years, 20 – 40 years and >40 years. Categories of ownership were private grant aided, private non grant-aided and state established. The term "state established" was applied to forests that were planted by the state but may have been sold into private ownership prior to deforestation activity. Examples included the construction of windfarms on former state owned forest land. Recording of LUTs were based on a modified version of NFI land-use reporting categories, namely grassland, wetland, built land rural, built land urban, windfarm, road, green space, quarry, peat, cropland and other.

Ancillary records

A number of pre-existing sources of information describing the deforestation area are available for the Republic of Ireland for the study period. These records were used to identify additional deforestation areas not initially captured during the photointerpretation process.

CORINE

The European Commission and European Environmental Agency established the CORINE programme in 1985 with the aim of providing land-cover information for Europe (Bossard et al. 2000). Based on interpretation of satellite imagery, pan-European datasets of classified land-cover types are available for 1990 (CORINE land cover (CLC) 1990), 2000 (CLC 2000), 2006 (CLC 2006) and 2012 (CLC 2012). For this

study, datasets describing differences between the CLC 2000 - 2006 and the CLC 2006 – 2012 imagery were used to identify areas changing from forest to non-forest land-use during the study periods. Each CORINE polygon identified as potentially changed was validated using contemporary OSI and Bing Maps high resolution aerial imagery. Where the spatial extent of CORINE derived deforestation differed, or where no deforestation activity was evident based on imagery, CORINE deforestation polygons were modified or excluded from the dataset.

Felling licences

In the Republic of Ireland, the Forestry Act of 1946 legally requires land owners to obtain consent for the majority of deforestation activities in the form of Limited Felling Licences (LFLs). The regulation of the felling licences is the reponsibility of the Forest Service Division within the Department of Agriculture, Food and the Marine. Certain deforestation activities do not require a felling licence, such as public road building or the felling of trees to facilitate the distribution of electricity. Since 2007, records of these LFLs contain information regarding the area and location of deforested land. Afforested areas less than 10 years old are exempt from LFL requirement for deforestation activities. However, most forest areas less than 10 years-old are subject to grant and premium payments under a national afforestation scheme. In such cases, forest owners are obliged to notify the Forest Service if these areas are removed from forest land-use. Since 2007, the Forest Service maintained records of lands taken out (known as LTOs) of forest land-use. For this study, the spatial extent of LFL and LTO deforested areas in the study regions were digitised in ArcGIS 10.2 based on hard-copy maps provided in licence applications. As with CORINE data, where the spatial extent of deforestation differed based on imagery interpretation, deforestation polygons were modified or removed.

Bog restoration

From 2002 to 2008, Coillte Teoranta (the semi-state forestry company) and various other agencies undertook large-scale raised and blanket bog habitat restoration projects under the European Union LIFE funding mechanism. Spatial information on restoration activities in the study regions involving the conversion of forest land-use to wetland (bog/heath) land-use was obtained from Coillte Teoranta.

Other data sources

Periodic updates to the Forest Service national forest cover map (Forestry 2012) were made throughout the study period. Therefore, information on potential deforestation areas was available by extracting forest areas that were present in previous national forest cover datasets but absent in Forestry 2012. These areas were examined using imagery to verify deforestation activity and determine the LUT. In addition,

results from the most recent NFI indicated a large proportion of deforestation area coming from forest areas clear-felled and not replanted within a five-year period. Supplementary data on these potential deforestation areas was obtained through the Forestry 2012 dataset. Using land-cover attributes in Forestry 2012, areas listed as forest in 2000, clear-felled in 2005, and remaining clear-felled in 2010 and 2012 were extracted. Due to difficulties differentiating clear-felled areas from recently replanted forest using imagery, all such areas were ground surveyed to verify current land-use. The full extent of deforestation events highlighted by the NFI was also digitised in ArcGIS 10.2 based on the most recent imagery.

The Deforestation Map

Deforestation areas based on the above sources were appended to the photointerpretation dataset to create the Deforestation Map, a geodatabase of deforestation events in Ireland for the 2000 to 2012 period. In cases where the occurrence of deforestation or LUT was uncertain, polygons were reviewed by other expert photo-interpreters. Where uncertainty remained following re-interpretation, ground surveys were carried out. In total, 233 sites were ground surveyed to verify deforestation activity (Figure 2). To test classification accuracies, a stratified random sample of deforestation polygons was selected and information such as forest age, type and land-use transition were cross-checked by an independent analyst to determine the percentage agreement in the attributes assigned. Overall, percentage agreement varied from 80% for the forest age category to 96% for the forest ownership category. An accuracy assessment of deforestation areas was carried out using imagery point sampling and ground survey plots. The Irish national forest vector dataset (Forest2000) was used as reference data for forest land-use area for the year 2000. Within Forest2000, 7,936 stratified randomly located points were visually interpreted using Google Earth imagery, which was used as a reference for 2012 land-use (sampling was restricted to areas where post 2011 imagery was available in Google Earth). Areas where a clear, permanent, non-forest land-use was evident in 2012 were recorded as deforestation. LUCAS (Land Use/Cover Area frame Survey) plots (n = 219) and NFI forest plots (n = 1,845) were added to the accuracy assessment dataset (total n = 10,000). Following comparison between the Deforestation Map and the reference dataset, the producer's accuracy (the proportion of deforested points based on the reference data that is also mapped as deforestation), user's accuracy (the proportion of the area mapped as deforestation that is actually deforested based on reference data) and overall accuracy (the proportion of the area mapped correctly) were calculated. For uncertainty analysis, the 95% confidence interval of the error-adjusted deforestation area estimate was calculated following Olofsson et al. (2013).

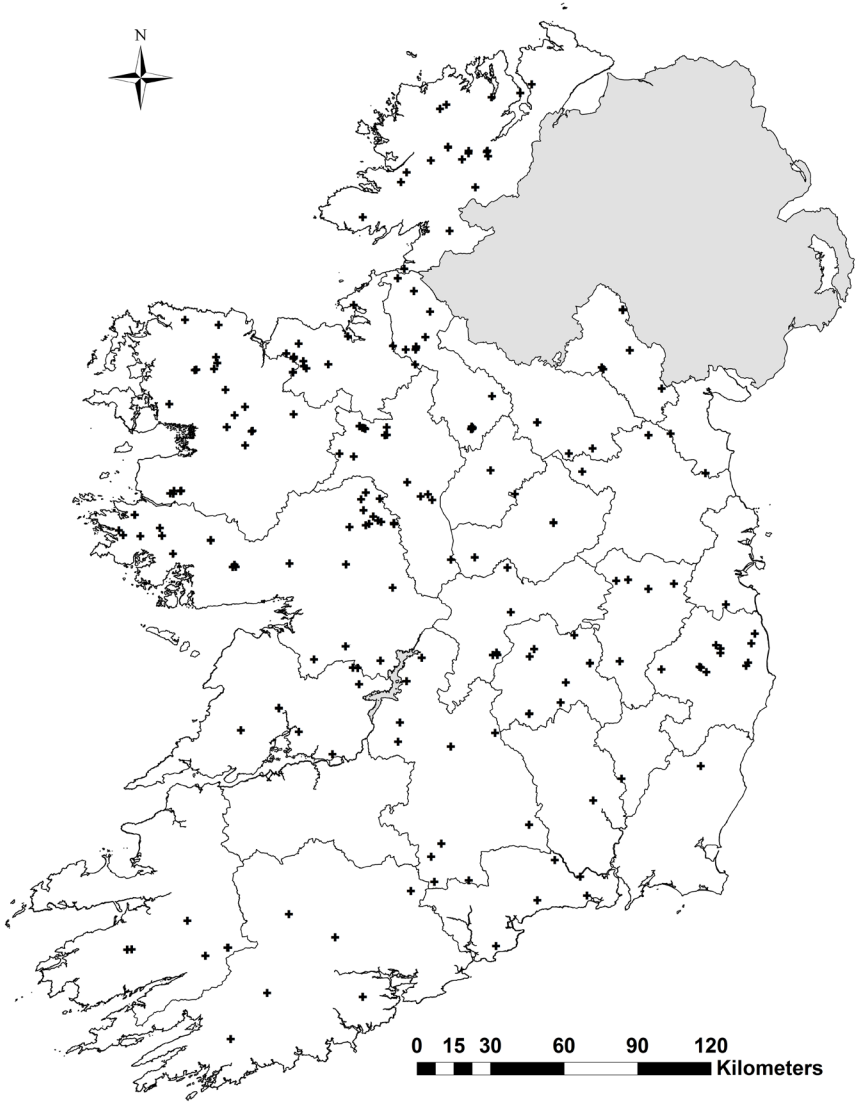

Figure 2: *Spatial distribution of 233 ground survey sites used to validate deforestation events.*

Results

In total, 5,457.1 ha of land deforested during the 2000 – 2012 period were explicitly identified (Table 1). The counties with the highest total area of deforestation for the period were Galway (1,008.5 ha) and Mayo (809.1 ha). These counties had approximately twice the area of deforested land in comparison to the next highest county (Cork: 443.1 ha; Table 1). In contrast, the counties with the lowest total deforestation

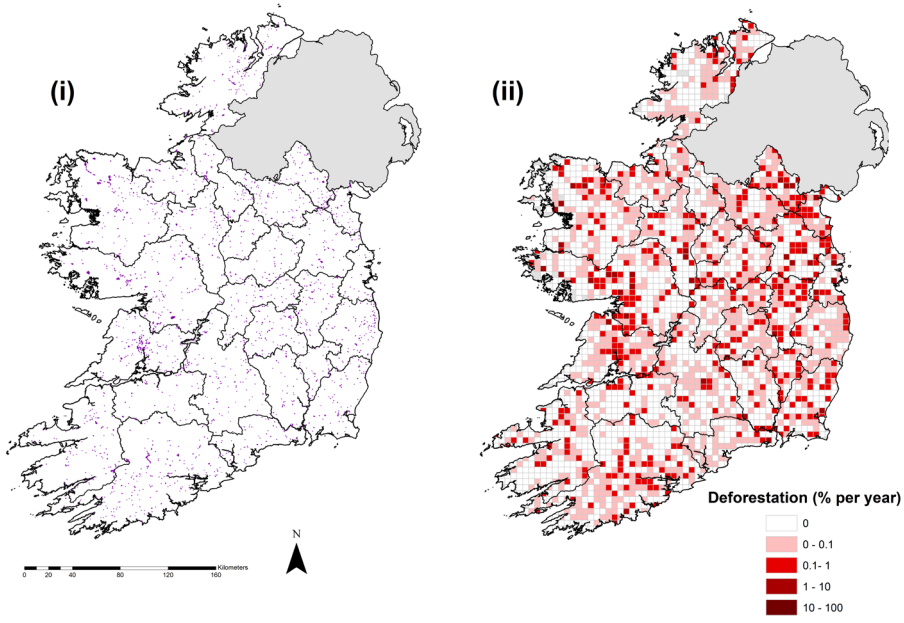

Figure 3: *(i) The Deforestation Map indicating the spatial distribution of deforestation events during the period 2000 – 2012 (areas are slightly exaggerated for visual purposes) and (ii) the gross annual deforestation rate on a 5 × 5 km grid. White indicates squares with no deforestation.*

area were Longford (28.6 ha) and Dublin (31.9 ha). Relative to the existing area of forest in the county, Monaghan and Louth had the highest level of deforestation with gross annual deforestation rates of 0.248% and 0.243% respectively. Limerick and Longford had the lowest rates of gross annual deforestation, 0.022% and 0.029% respectively (Table 1). The gross annual national deforestation rate for Ireland for the 2000 – 2012 period was 0.075%. The national average size of deforestation event was 1.81 ha, however this varied widely between counties. For example, the mean size of deforestation events in Mayo was 3.97 ha, whereas in Longford, it was only 0.73 ha (Table 1). Nationally, the median size of deforestation event was just 0.62 ha.

As shown by the Deforestation Map (Figure 3 (i)), the occurrence of deforestation events was relatively evenly distributed across the Irish landscape. As expected, areas of a high density of deforestation events were associated with areas of high forest cover. Figure 3 (ii) displays the gross annual deforestation rate throughout the country on 5 × 5 km grid. Based on this map, some clusters of high deforestation areas are visible, such as central Clare and the Louth-Monaghan border regions.

The overall temporal trend in deforestation area was an increase from the 2000 – 2005 period (415.5 ha yr^{-1}) to the 2005 – 2010 period (565.6 ha yr^{-1}) followed by a decline in

deforestation for the 2010 – 2012 period (350.9 ha yr^{-1}). However, variation between counties was evident; in Monaghan deforestation decreased from 20.3 ha yr^{-1} in the 2000 – 2005 period to 5.2 ha yr^{-1} in the 2005 – 2010 period and increased to 19.4 ha yr^{-1} in the 2010 – 2012 (Table 1). Overall, the cumulative deforestation area during the 2000 - 2012 period was minimal in comparison to the cumulative afforestation area for the same period (Figure 4).

In terms of total area, forest to grassland (30.1%) and forest to wetland (27.9%) were the most common deforestation LUTs, each accounting for more than double the next most common deforestation LUT (built land rural: 13.1%; Figure 5)). Built land categories included all human settlement excluding windfarms, roads, recreational green spaces and quarries. Examples of built land transitions included housing developments, water treatment works and landfill sites. Combined, built land rural and built land urban transitions accounted for 14.4% of deforested land. Conversion of forest to cropland was negligible, accounting for only 0.24% of the total deforestation area (Figure 5).

Almost half of the total deforested area occurred in state established forests (2,757.2 ha), with the majority of this taking place in conifer dominated forests (Figure 6). Deforestation area of broadleaf dominated state established forests was only 27.7 ha. The extent of deforestation, which occurred in privately owned forests that were established with some form of grant aid was smaller (1,122.5 ha). Within this, 730.7 ha occurred in conifer dominated forests, 229 ha in broadleaf

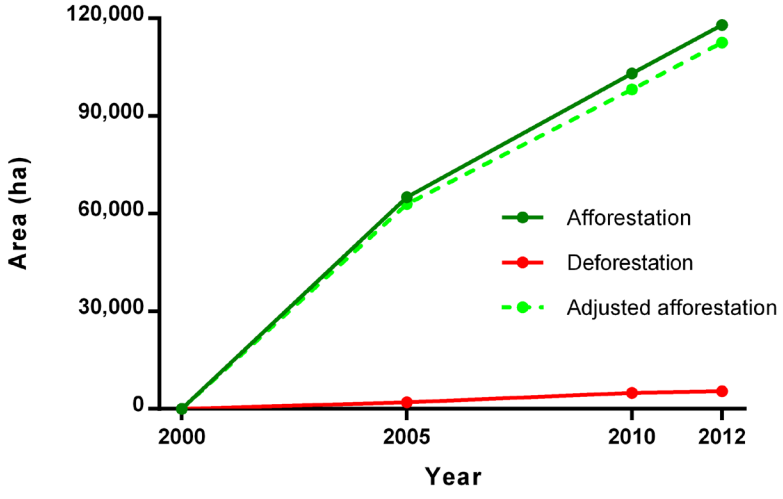

Figure 4: *Cumulative afforestation, deforestation and adjusted afforestation (the afforested area minus the area of deforested land; ha) in the Republic of Ireland for the period 2000 – 2012.*

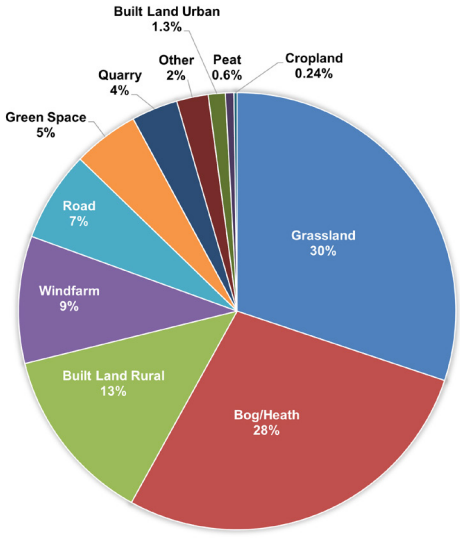

Figure 5: *Proportional area of post deforestation land uses.*

dominated forests and 162.8 ha in mixed forests. During the study period, 1,566.9 ha of deforestation took place on privately owned non-grant aided forests and, the majority of this occurred in broadleaf dominated forests (1,284.5 ha) (Figure 6).

An error-adjusted change area and associated confidence intervals were calculated for the Deforestation Map based on the error matrix following the methods outlined in Olofsson et al. (2013). The accuracy assessment revealed significant errors of omission (27%) but few errors of commission (2.5%), resulting in an error-adjustment of total deforestation area from 5,457.1 ha to 7,465 ±785 ha. The error-adjusted gross annual national deforestation rate for Ireland for the 2000 – 2012 period was 0.103 %.

Discussion

As Ireland's national forest area continues to increase, so does the need to develop national forest monitoring capabilities. In this study, novel and existing records of deforestation activities were combined with high-resolution imagery interpretation to quantify loss in forest land-use in Ireland for the period 2000 – 2012. This paper presents an important development in our understanding of contemporary land-use change in Ireland; the first spatially explicit national characterisation of deforestation areas.

Temporal and spatial patterns in deforestation

Nationally, a relatively stable annual deforestation rate was recorded throughout

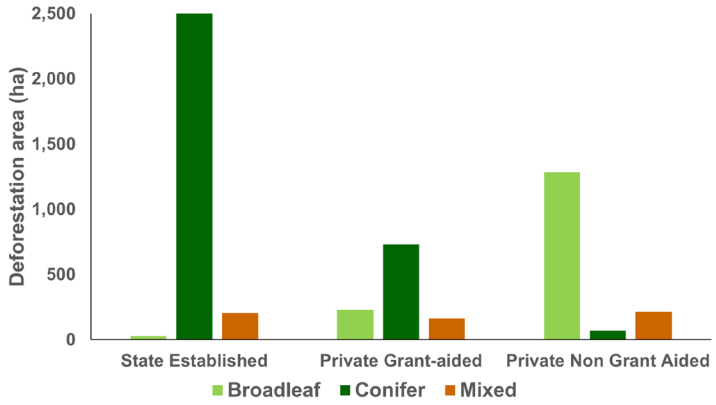

Figure 6: *Deforestation area (ha) from different forest type (broadleaf, conifer and mixed) and ownership (state established, private grant-aided and private non grant-aided) categories.*

the study period (Table 1 and Figure 4). The increase in the national deforestation rate from the 2000 – 2005 to the 2005 – 2010 period was related to large-scale bog restoration programmes, carried out by Coillte Teoranta and other agencies. Raised and blanket bog habitat restoration activities included the clear-felling of coniferous forest and conversion to their pre-afforestation land-cover of bog/heath. Although some felling operations took place pre-2005, an increase in forest to wetland conversions occurred for the 2005 – 2010 period. These restoration programmes had a significant influence on the overall findings of the study, particularly for attributes such as the average size of deforestation event and deforested land ownership. Compared to other recorded events, bog restoration deforestation areas were large (>30 ha). Exclusion of bog restoration areas from the Deforestation Map dataset would result in a reduction in the national average size of deforestation event from 1.81 ha to 1.51 ha. Omitting bog restoration areas from the analysis would reduce the proportion of "state established" forests from 50% to 34% of the total deforestation area.

A high proportion of the deforestation area was attributable to broadleaf forests in non-grant aided private ownership (Figure 6). Broadleaf forests constitute 25% of the national forest area and semi-natural broadleaf forests constitute only 2% of the national forest area (Forest Service 2013, Perrin et al. 2008). Sixty percent of deforested non grant-aided privately owned broadleaf forests were converted to agricultural grassland (Devaney et al. unpublished data). From a conservation perspective, the high rate of deforestation of broadleaf forests is unexpected and has implications, particularly in the context of habitat protection legislation such

Table 1: *Details of deforestation area (ha yr^{-1}), rate (%) and mean size of event (ha) in Ireland (per county) for the period 2000 – 2012.*

County	**Total deforestation area** (ha)	**Deforestation area** (ha)			**Gross annual rate** (%)	**Mean area of event** (ha)
		2000 - 2005 (ha yr^{-1})	**2005 - 2010** (ha yr^{-1})	**2010 - 2012** (ha yr^{-1})		
Leitrim	97.6	1.2	9.6	21.7	0.031	1.22
Longford	28.6	2.0	2.4	3.4	0.029	0.73
Meath	140.9	2.8	23.1	5.8	0.094	1.57
Louth	70.9	2.9	8.4	6.9	0.243	1.07
Cavan	105.5	3.0	17.3	2.1	0.052	0.90
Dublin	31.9	3.7	2.6	0.0	0.051	1.33
Carlow	58.4	3.7	7.0	2.4	0.058	1.22
Offaly	102.4	4.6	14.6	3.3	0.035	1.11
Limerick	70.3	4.8	5.6	9.2	0.022	1.03
Westmeath	109.0	5.1	15.7	2.6	0.069	1.65
Sligo	119.1	6.6	8.1	22.7	0.048	1.59
Laois	126.5	8.1	15.2	4.9	0.042	1.32
Roscommon	174.5	8.6	22.0	10.6	0.056	2.05
Wicklow	183.8	9.7	23.8	8.1	0.043	1.63
Tipperary	172.6	10.8	19.4	86.3	0.030	1.11
Waterford	94.8	10.8	7.1	2.7	0.030	1.30
Kilkenny	114.7	11.3	10.4	3.2	0.050	2.12
Donegal	207.2	11.7	27.2	6.5	0.031	0.89
Wexford	150.0	14.2	11.9	9.8	0.090	1.44
Kildare	215.1	19.8	16.1	17.7	0.172	2.33
Monaghan	166.6	20.3	5.2	19.4	0.248	1.63
Kerry	274.7	26.8	14.4	34.2	0.043	1.68
Cork	443.1	39.4	40.2	22.5	0.044	1.65
Clare	381.2	39.5	32.4	10.8	0.061	1.69
Mayo	809.1	68.8	84.4	21.5	0.130	3.97
Galway	1,008.5	75.2	121.6	12.3	0.141	3.63
Total	5,457.1	415.5	565.6	350.9	0.075	1.81

as the EU Habitats Directive and agri-environment schemes such as the Rural Environmental Protection Scheme. Given that broadleaf forests often occur on mineral soil types, which are conducive to agricultural production, it is likely that these areas are at a higher risk of deforestation to grassland.

An increase in conversions from forest to "built land rural" also occurred between the 2000 – 2005 period and the 2005 – 2010 period, followed by a sharp decline for 2010 – 2012 (Figure 7). During the 2000 – 2007 period, Ireland's flourishing economy was associated with an increase in the construction of private housing, commercial property and public infrastructure. Although development peaked in 2007, high

levels of construction continued into 2009 (Kitchin et al. 2014). However, the well documented financial crash and economic decline led to a downturn in the construction sector (Whyte et al. 2013) which is reflected in a reduction in the conversion of forest land to built land rural for the same time period.

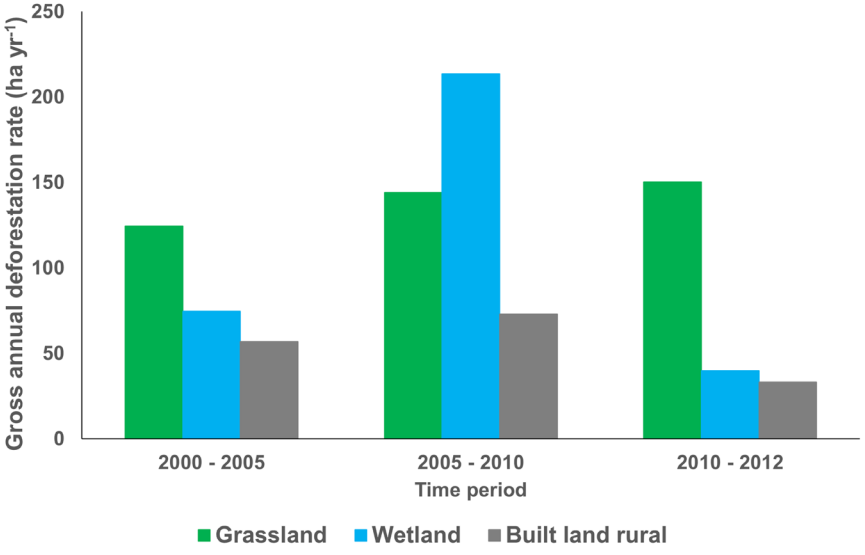

Figure 7: *Gross annual deforestation rate (ha yr^{-1}) for the three principal post deforestation land-use categories (grassland, wetland and built land rural) for three time periods (2000 – 2005, 2005 – 2010, 2010 – 2012).*

High inter-county variation in the rate of forest loss indicates changing spatial and temporal pressures on forest land-use. For example, in Donegal, 32% of the total deforestation area was attributable to conversions to built land, with 18% attributable to forest-grassland LUTs. In Laois, only 12% of deforestation was associated with conversion to built land with forest-grassland being the principal land-use transition (51%). Regional clusters of deforestation activities were evident, including areas surrounding Ennis, Co. Clare and on the Louth – Monaghan border. Deforestation activities in both these areas principally involved the conversion of forest to grassland. Spatial patterns of forest land-use changes are likely to reflect regional variation in factors such as economic development and productivity of agricultural land. The Deforestation Map geodatabase facilitates the assessment of regional influences on forest land-use change events. Further research is required to investigate the regional drivers of deforestation and to develop tools that may predict future deforestation hot spots such as in De la Heras et al. (2012) and Sanchez-Cuervo et al. (2013).

Comparison with National Forest Inventory estimates

For the 2000 – 2012 period, a total of 5,457.1 ha of deforested land were identified by this study. This figure is substantially less than the 15,600 ha ± 4,931 ha of deforested land estimated by the NFI for the same period (Forest Service 2013, Forest Service 2007), which is significant in the context of UNFCCC reporting. Currently, post 2000 deforestation area reported in Ireland's UNFCCC National Inventory Report is based on changes in land-use of NFI permanent sample plots. Although this approach is used in many countries (Tomppo et al. 2010), for countries where the deforestation rate is low (<1%), small sample sizes may result in high levels of uncertainty associated with estimates (Dymond et al. 2008, Magnussen et al. 2005). The large uncertainty associated with Ireland's NFI deforestation estimates is due to the low incidence of deforestation in the sample plots (0.8 - 1.3%) (Forest Service 2013). The benefit of applying a "wall-to-wall" approach presented here is that a map accuracy assessment can be carried out using standard methods. The accuracy assessment of the Deforestation Map indicted that the overall accuracy was 98% and the error of omission (the proportion of deforested points in the reference data that are not actually mapped as deforestation) was 27%. When an error-adjusted Deforestation Map area (7,465.63 ±785.67 ha) is applied, the estimate remains below the minimum area confidence interval of the NFI (what is NFI) estimate, indicating that NFI derived data over-estimates national deforestation area. The use of other national deforestation statistics from sources such as limited felling licences are likely to underestimate deforestation areas as unlicensed activities are unaccounted for. Levy and Milne (2004) concluded that in Britain, deforestation estimates based on felling licences most likely represented a minimum, as unlicensed felling also occurred but to an unknown extent. Inconsistencies between the Deforestation Map, NFI estimates and national deforestation statistics, though expected, nevertheless highlight the need for a modified national deforestation accounting approach.

Future deforestation monitoring in Ireland

For the purposes of UNFCCC reporting, updates of national deforestation areas would be challenging using the Deforestation Map approach due to the low temporal availability of high resolution imagery and resource constraints relating to time intensive wall-to-wall manual photo-interpretation (Devaney et al. 2015a). Nonetheless, a national scale photointerpretation of deforestation areas could potentially be repeated on a cyclical basis using updated national imagery datasets. Still, remote sensing is an effective tool for monitoring forest area changes in an objective and transparent way (McInerney et al. 2011). Due to developments in technical capabilities, the use of high resolution satellite-based optical remote sensing is now well established in operational forest monitoring systems worldwide, e.g. India (Forest Service of India 2004), Brazil (INPE 2013) and New Zealand

(Dymond et al. 2012). However, the application of optical remote sensing is limited in countries such as Ireland, which have near-constant cloud coverage. Microwave remote sensing systems however are not as influenced by atmospheric conditions and may be more appropriate for tracking Irish landscape changes (Barrett et al. 2014, Devaney et al. 2015b). The national Deforestation Map will provide a valuable record of forest loss, which can be used to validate any future remote sensing deforestation monitoring approaches. Ultimately, as UNFCCC reporting is on the basis of land-use and not land-cover, a combination of remotely sensed information and ground-based observations is the most practicable approach in determining deforestation areas and associate land-use transitions.

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References

Barrett, B., Nitze, I., Green, S. and Cawkwell, F. 2014. Assessment of multi-temporal, multi-sensor radar and ancillary spatial data for grasslands monitoring in Ireland using machine learning approaches. *Remote Sensing of Environment* 152: 109–124.

Bossard, M., Feranec, J. and Otahel, J. 2000. *CORINE land cover technical guide: Addendum 2000*. European Environment Agency, Copenhagen.

Byrne, K. 2011. The role of plantation forestry in Ireland in the mitigation of greenhouse gas emissions. *Irish Forestry* 67: 86–96.

de las Heras, A., Lake, I.R., Lovett, A. and Peres, C. 2012. Future deforestation drivers in an Amazonian ranching frontier. *Journal of Land Use Science* 7: 365–393.

Devaney, J., Redmond, J. and O'Halloran, J. 2015. Contemporary forest loss in Ireland; quantifying rare deforestation events in a fragmented forest landscape. *Applied Geography* 63: 346–356.

Devaney, J., Barrett, B., Barrett, F., Redmond., J. and O'Halloran, J. 2015. Forest cover estimation in ireland using radar remote sensing: a comparative analysis of forest cover assessment methodologies. *PloS ONE*, 10, e133583.

Duffy, P., Hanley, E., Hyde, B., Ponzi, J., O'Brien, P., Cotter, E., and Black, K. 2014. *Ireland National Inventory Report 2014*, Greenhouse Gas Emissions 1990–2012. Reported to the United Nations Framework Convention on Climate Change. Environmental Protection Agency, Wexford, Ireland.

Dymond, J.R., Shepherd, J.D., Arnold, G.C. and Trotter, C.M. 2008. Estimating area of forest change by random sampling of change strata mapped using satellite imagery. *Forest Science* 54: 475–480.

Dymond, J.R., Shepherd, J.D., Newsome, P.F., Gapare, N., Burgess, D.W. and Watt, P. 2012. Remote sensing of land-use change for Kyoto Protocol reporting: the New Zealand case. *Environmental Science and Policy* 16: 1–8.

Forest Service of India. 2004. *State of Forest Report 2003*. Ministry of Environment and Forest, Dehra Dun, India.

Forest Service. 2007. *National Forest Inventory Republic of Ireland – Results*. Department of Agriculture, Food and the Marine, Johnstown Castle, Wexford, Ireland.

Forest Service. 2013. *Ireland's National Forest Inventory Results 2012*. Department of Agriculture, Food and the Marine, Johnstown Castle, Co. Wexford, Ireland.

Forest Service. 2014. *Forests, Products and People. Ireland's Forest Policy – a Renewed Vision*. Available at https://www.agriculture.gov.ie/media/migration/forestry/forestpolicyreviewforestsproductsandpeople/00487%20Forestry%20Review%20-%20web%2022.7.14.pdf [Retrieved April 2014].

Gallagher, G., Dunne, S., Jordan, P. and Stanley, B. 2001. *Ireland's Forest Inventory and Planning System*. Forest Service, Department of Agriculture and Food, Johnstown castle Estate, Co. Wexford. Ireland.

INPE. 2013 *Monitoramento da Floresta Amazônica brasileira por satélite*. Instituto Nacional de Pesquisas Espaciais Projeto Prodes. Available at http://www.obt.inpe.br/prodes/index.php [Retrieved October 2013].

Kitchin, R., O'Callaghan, C. and Gleeson, J. 2014. The new ruins of Ireland? Unfinished estates in the post-Celtic Tiger era. *International Journal of Urban and Regional Research* 38: 1069–1080.

Levy, P. and Milne, R. 2004. Estimation of deforestation rates in Great Britain. *Forestry* 77: 9–16.

Magnussen, S., Kurz, W., Leckie, D.G. and Paradine, D. 2005. Adaptive cluster sampling for estimation of deforestation rates. *European Journal of Forest Research* 124: 207–220.

McInerney, D., Suarez, J. and Nieuwenhuis, M. 2011. Extending forest inventories and monitoring programmes using remote sensing: a review. *Irish Forestry* 68: 6–22.

Mitchell, F. 2000. The development of Ireland's tree cover over the millennia. *Irish Forestry* 57: 38–46.

Olofsson, P., Foody, G.M., Stehman, S.V. and Woodcock, C.E. 2013. Making better use of accuracy data in land change studies: estimating accuracy and area and quantifying uncertainty using stratified estimation. *Remote Sensing of Environment* 129: 122–131.

Penman, J., Gytarsky, M., Hiraishi, T., Krug, T., Kruger, D., Pipatti, R, Buendia, L., Miwa, K., Ngara, T., Tanabe, K. and Wagner, F. (Eds). 2003. *Good practice guidance for land use, land-use change and forestry*. Institute for Global Environmental Strategies. Hayama, Japan.

Perrin, P., Martin, J., Barron, S., O'Neill, F., McNutt, K. and Delaney, A. 2008. *National Survey of Native Woodlands 2003–2008: Volume I: Main report*. National Parks and Wildlife Service, Dublin.

Sanchez-Cuervo, A.M. and Aide, T.M. 2013. Identifying hotspots of deforestation and reforestation in Colombia (2001–2010): implications for protected areas. *Ecosphere* 4: art143.

Tomppo, E., Gschwantner, M., Lawrence, M. and McRoberts, R.E. 2010. *National Forest Inventories Pathways for Common Reporting*. Springer: Dordrecht.

Whyte, K., Daly, H.E. and Ó Gallachóir, B.P. 2013. Modelling HGV freight transport energy demand in Ireland and the impacts of the property construction bubble. *Energy* 50: 245–251.