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21st Century Deforestation in Ireland

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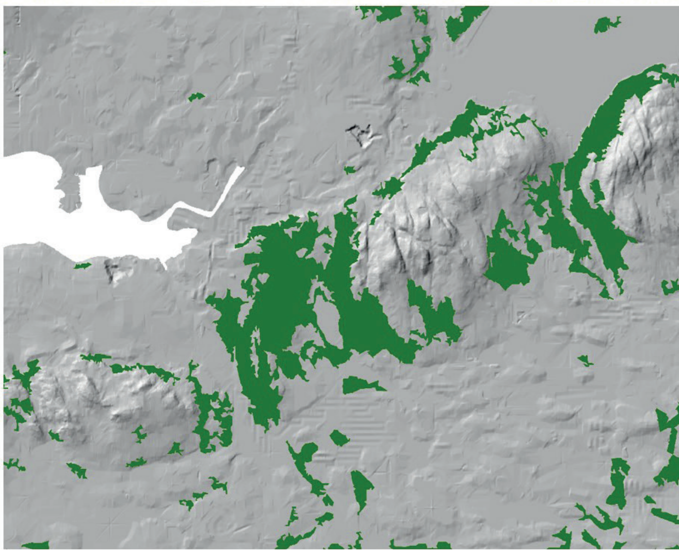

Roinn Cumarsáide, Gníomhaithe
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21st Century Deforestation in Ireland

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EPA Research Report

Prepared for the Environmental Protection Agency

by

University College Cork; Forest Service, Department of Agriculture, Food and the Marine; and University of Glasgow

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The EPA Research Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

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Executive Summary

As a result of extensive afforestation over recent decades, Ireland's forest carbon makes a substantial contribution to national greenhouse gas (GHG) reduction targets (Byrne, 2011). Although the total area of forest in Ireland is undoubtedly expanding, some recent evidence suggests that the annual rate of gross deforestation is increasing (Forest Service, 2013). Deforestation could have a significant impact on forest-related GHG emissions in Ireland's National Inventory Report to the United Nations Framework Convention on Climate Change (UNFCCC). However, large uncertainties are associated with current estimates of national deforestation. Indeed, heretofore, no spatially explicit quantification of contemporary deforestation in Ireland existed. Hence, the objectives of this study were to (1) create a national deforestation map for the period 2000–2012 and characterise the extent and nature of deforestation events, and (2) assess the validity of existing estimation methodologies. A preliminary assessment of the use of satellite synthetic aperture radar (SAR) for forest cover and deforestation monitoring in Ireland was also carried out.

Using a combination of aerial photo interpretation, high-resolution imagery and ancillary datasets, a spatially explicit national map of deforestation was created. A total of 3022 individual deforestation events were identified for the 2000–2012 study period, constituting 5457.1 ha of deforested land. There was no consistent pattern of increasing deforestation rate over the duration of the study period, although the deforestation rate did increase between the 2000–2005 and 2005–2010 periods. This increase was followed by a reduction in the rate of forest to non-forest conversions during the 2010–2012 period. The principal post-deforestation land-use transitions were forest to settlement and forest to grassland. A large area of forest to wetland transitions was attributable to bog habitat restoration activities, whereby large areas of non-native plantation forests were removed and restored to their previous bog land cover. The rate of deforestation of broadleaf forests was considerably higher than in mixed and conifer-dominated forests, despite broadleaf forests accounting for only 25% of the national forest area.

Following a comprehensive accuracy assessment, the national deforestation map area was error adjusted from 5457.1 ha to 7465.63 ha (±785.67 ha). This area is below the lower 95% confidence interval of the National Forest Inventory (NFI) deforestation estimate for the same period (10,669 ha), suggesting that the NFI may have overestimated deforestation areas. In contrast, the deforestation map-derived estimate was much greater than estimates derived from CORINE (Co-ordination of Information on the Environment) and other national statistics such as felling licences, indicating omissions in these datasets. A preliminary study of the potential application of SAR to forest monitoring in Ireland indicated that forest cover mapping with high accuracies can be achieved using L-band SAR data. While our study shows the value of SAR for forest *cover* change detection, reporting forest *land-use* change for UNFCCC reporting is more problematic given the clear-fell replant silvicultural system operating in much of Ireland's forests. Nonetheless, used in combination with photointerpretation, ground survey and ancillary data, radar remote sensing offers a valuable tool for future forest change accounting in Ireland.

1 Introduction

1.1 Background

The conversion of forest land to non-forest land contributes to 6–17% of global anthropogenic CO_2 emissions to the atmosphere (van der Werf *et al.*, 2009; Ashton *et al.*, 2012) and is a principal driver of human-induced climate change (Bonan, 2008). 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 greenhouse gas (GHG) emissions and removals. As a net carbon sink, Ireland's forests make a significant contribution to national GHG reduction targets (Byrne, 2011), and quantification of temporal and spatial changes in forest land use in Ireland is required to meet Kyoto Protocol reporting obligations.

Since the turn of the 20th century, forest cover in Ireland has increased from less than 1% to almost 11% today through extensive afforestation. Although the overall national forest area in Ireland is still expanding, recent evidence suggests that the rate of gross annual deforestation is also increasing (Forest Service, 2013; Duffy *et al.*, 2014). Results from Ireland's National Forest Inventory (NFI) indicate that 15,600 ha (± 4931 ha) of forest land was deforested during the 2000–2012 period. Such levels of deforestation could have a significant impact on forest-related GHG emissions in Ireland's National Inventory Report (NIR) to the UNFCCC.

It is important to note that, for most Irish deforestation reporting mechanisms, the UNFCCC definition of deforestation is adopted: "the direct human-induced conversion of forested land to non-forested land" (Penman *et al.*, 2003). As long as replanting occurs within a 5-year period, forest management operations such as clear-felling do not constitute deforestation (Figure 1.1). Features that form part of the forest land-use infrastructure, such as the creation of forest roads and ride lines, are considered components of forest land use and are also not deemed deforestation activities. Examples of contemporary deforestation (permanent land-use changes) include the construction of windfarm infrastructure, roads, human settlements on forest land and the conversion of forest to agricultural land uses.

While evidence exists to suggest an increase in the rate of deforestation in Ireland over the last decade,

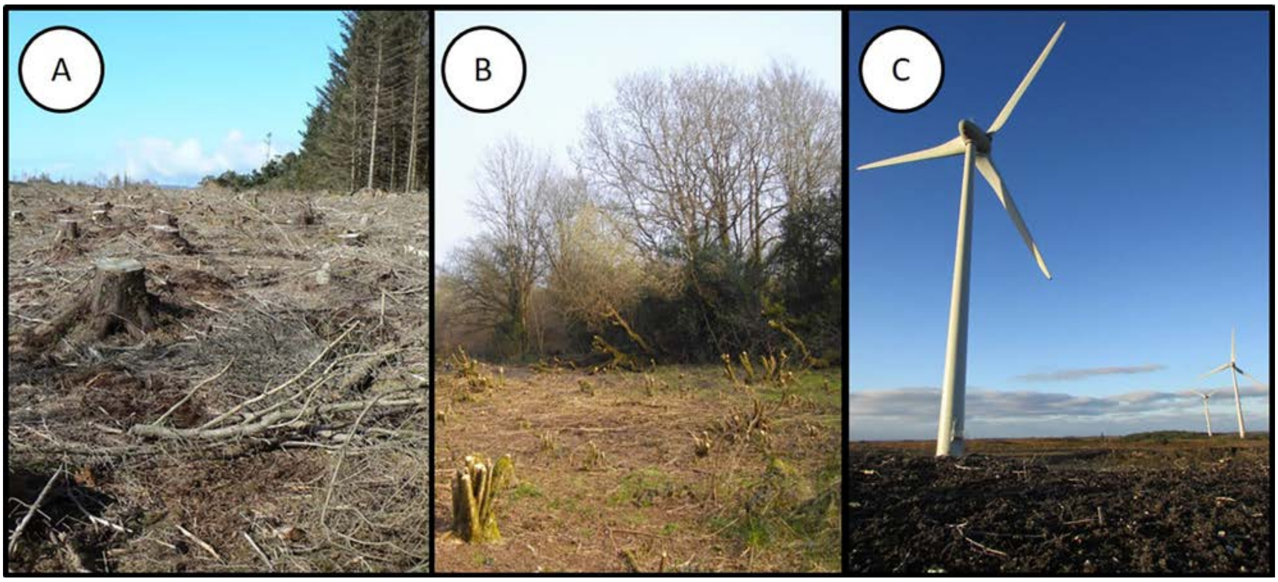

Figure 1.1. Types of forest removal in Ireland. Clear-felling (A) forms part of the silvicultural system operated in many Irish forests. If clear-felled areas are replanted within 5 years, they do not constitute deforestation. Permanent changes in land use constituting deforestation include the conversion of forest to agricultural land (B) and the construction of wind turbines on forest land (C).

large uncertainties are associated with available deforestation area estimates. NFI information forms the basis of deforestation reporting under the land use, land-use change and forestry (LULUCF) sector of Ireland's NIR to the UNFCCC. As part of the NFI, over 1800 permanent sample forest plots are resampled on a periodic basis and their land use is determined by ground survey and imagery interpretation [modified approach 3 of the Intergovernmental Panel on Climate Change (IPCC) Good Practice Guidelines (GPGs) (Penman *et al*., 2003)]. For countries where deforestation is a relatively rare event, estimates based on this methodology are associated with large uncertainties. For example, for the period 2000–2006, the total Irish national deforestation area ±95% confidence interval was 6000 ha (±3000 ha) (Forest Service, 2007). Co-ordination of Information on the Environment (CORINE) satellite-based data are also currently used to track pre-1995 deforestation in Ireland (Duffy *et al*., 2014). On account of classification and resolution issues, a number of studies have highlighted the inappropriateness of using CORINE data for reporting areas under LULUCF (Cruickshank and Tomlinson, 1996; Hazeu and de Wit, 2004; Black *et al*., 2008). As with a number of other countries (e.g. United Kingdom) (Brown *et al*., 2012), previous submissions of Ireland's NIR included deforestation information based on felling licence records. However, felling licence information does not capture any unlicenced deforestation activity and it is likely that these records underestimate the national deforestation area.

Given the outlined uncertainties associated with current deforestation estimates, investigation of new methodologies is required to inform future land-use change accounting approaches. The availability of high-resolution aerial photography, satellite imagery and repeat NFI data offers a valuable opportunity to assess and improve the accuracy of reporting forest-related land-use change in Ireland. Indeed, heretofore, no spatially explicit characterisation of contemporary deforestation areas in Ireland existed. To address this knowledge gap, in 2012, the Deforestation Estimation and Mapping in Ireland (DEFORMAP) project was initiated. A combination of high-resolution aerial imagery and ancillary datasets has been used to provide a spatially explicit map of deforestation in Ireland for the period 2000–2012.

1.2 Project Objectives

The overall objective of the DEFORMAP project was to assess the accuracy and validity of methods used to track deforestation in Ireland. To achieve this aim, the nature and extent of contemporary deforestation in Ireland for the period 2000–2012 was quantified. Based on our findings, a set of recommendations to improve the accuracy of reporting forest-related land-use change in Ireland are outlined (Chapter 5).

Specific project objectives included:

- To deliver a spatially explicit, high-resolution national deforestation map for Ireland for the 2000–2012 period.
- To conduct a thorough quality assurance and accuracy assessment procedure for the newly created national deforestation map, including comprehensive field survey.
- To assess spatial and temporal trends in the extent and cause of contemporary deforestation events in Ireland.
- To report on the accuracy of existing national deforestation statistics, including felling licence information, NFI estimates and deforestation areas derived from CORINE data.
- To assess the potential of L-band synthetic aperture radar (SAR) satellite data for deforestation mapping in Ireland.
- To provide a set of recommendations to improve future deforestation reporting in Ireland.

2 Quantifying 21st Century Deforestation in Ireland

2.1 Introduction

Ireland has a long history of dramatic spatial and temporal changes in forest cover. Following the withdrawal of ice *c*. 13,000 BP (before present) during the late glacial period, species such as sorrel (*Rumex* spp), dwarf willow (*Salix herbacea*) and juniper (*Juniperus* spp) colonised the treeless Irish landscape (Mitchell and Ryan, 1997; Perrin, 2003). By *c*. 9000 BP, Ireland was almost entirely forested, with species such as oak (*Quercus* spp), pine (*Pinus* spp) and elm (*Ulmus* spp) dominating (O'Carroll, 1984). However, by 5000 BP, expanding populations of Neolithic farmers led to the clearance of woodland to create areas for pastoral and arable farming (Neeson, 1991). This, combined with the expansion of blanket and raised bog habitats due to a wetter climate, and a sudden decline of elm forests (O'Connell and Molloy, 2001), caused a shift in the nature of Irish vegetation cover, resulting in a largely denuded forest landscape. The gradual clearance of forest for agriculture continued until relatively recent times and, at the beginning of the 20th century, forest cover in Ireland was < 1% (Mitchell, 2000). Since then, however, both state and private afforestation has increased forest cover to 10.5% (Forest Service, 2013), constituting one of the fastest ongoing land-use changes in Europe (Wilson *et al*., 2012).

As a party to the UNFCCC and the Kyoto Protocol, quantification of changes in forest land use in Ireland is required to meet international reporting obligations (UNFCCC, 1997). Previously considered to be relatively rare, recent evidence suggests that the rate of gross annual deforestation in Ireland is on the increase (Forest Service, 2013; Duffy *et al*., 2014). Since 1990, the rate at which forests are being converted to other land uses such as agriculture and settlement is increasing according to Ireland's NIR of GHG emissions (Duffy *et al*., 2014). The fragmented nature of forest cover in Ireland, and a national forest size definition of just > 0.1 ha, dictates that deforestation events are generally small and difficult to quantify. In comparison, the Food and Agriculture Organization of the United Nations (FAO) forest definition includes only wooded areas > 0.5 ha in size (FAO, 2010). Currently, on a national level, post-2000 deforestation areas reported in Ireland's NIR are based on changes in land use of NFI permanent sample plots (Duffy *et al*., 2014). This sample-based approach is used in many countries for estimation of deforestation areas (Tomppo *et al*., 2010). However, in countries like Ireland where the deforestation rate is low (< 1%), small sample sizes may result in high levels of uncertainty associated with estimates (Magnussen *et al*., 2005; Dymond *et al*., 2008).

Globally, approaches to reporting changes in forest area for the UNFCCC range from annual censuses and basic land-use data (Tier 1) to periodic ground surveys and satellite remote sensing (Tier 3) (Penman *et al*., 2003). Changes in the extent of forest cover are often quantified using a range of automated and semi-automated satellite-based remote sensing approaches. Although they have been successfully used to provide accurate estimates of deforestation, automated satellite-based approaches have limitations based on image resolution and classification inaccuracies. While such issues can be overcome using products such as Light Detection and Ranging (LiDAR) and object-based image analysis, these tools can require advanced expertise and resource investment not always available to regional or national reporting organisations. Furthermore, while automated satellite-based remote sensing can be effectively used to identify forest *cover* loss (e.g. Hansen *et al*., 2013), identifying changes in forest *land use* can be problematic, particularly in countries like Ireland, where the principal silvicultural method is clear-cutting followed by replanting. Clear-cutting is generally associated with a marked change in backscatter signal, but differentiating clear-cutting forest management operations from permanent land-use change may require ground survey or manual interpretation of imagery.

Manual interpretation of high-resolution aerial imagery has been shown to offer an accurate and cost-effective alternative to automated approaches to identifying regional land-use changes. Detecting land-use change using manual photointerpretation is generally carried out by interpreting a statistical sample of imagery of defined area (known as a photo-plot) or a stratified sample of points or pixels. When land-use change events are rare, sub-samples of imagery may not be sufficient to provide accurate quantification of change areas. In such cases, a complete, “wall-to-wall” manual interpretation of imagery may be required to provide a spatially explicit map of land-use change events, whereby all areas are assessed. Wall-to-wall manual photointerpretation for monitoring forest land-use change may be appropriate in regions or small countries like Ireland with rare, fine-scale deforestation events, and/or operating a predominantly clear-fell replant silvicultural system.

In this chapter, a national-scale assessment of contemporary deforestation in Ireland is presented. A combination of wall-to-wall aerial photointerpretation, high-resolution imagery and ancillary datasets have been used to provide a spatially explicit map of deforestation in Ireland for the period 2000–2012. In particular, emphasis is placed on the rate of gross annual deforestation per county, post-deforestation land-use transitions and the type and ownership status of deforested land.

2.2 Materials and Methods

Interpretation of high-resolution aerial imagery and ancillary records of deforestation events in Ireland was used to create a national deforestation map for the 2000–2012 period, hereafter termed the “Deforestation Map”. The process by which the Deforestation Map was created is outlined below and in Figure 2.1.

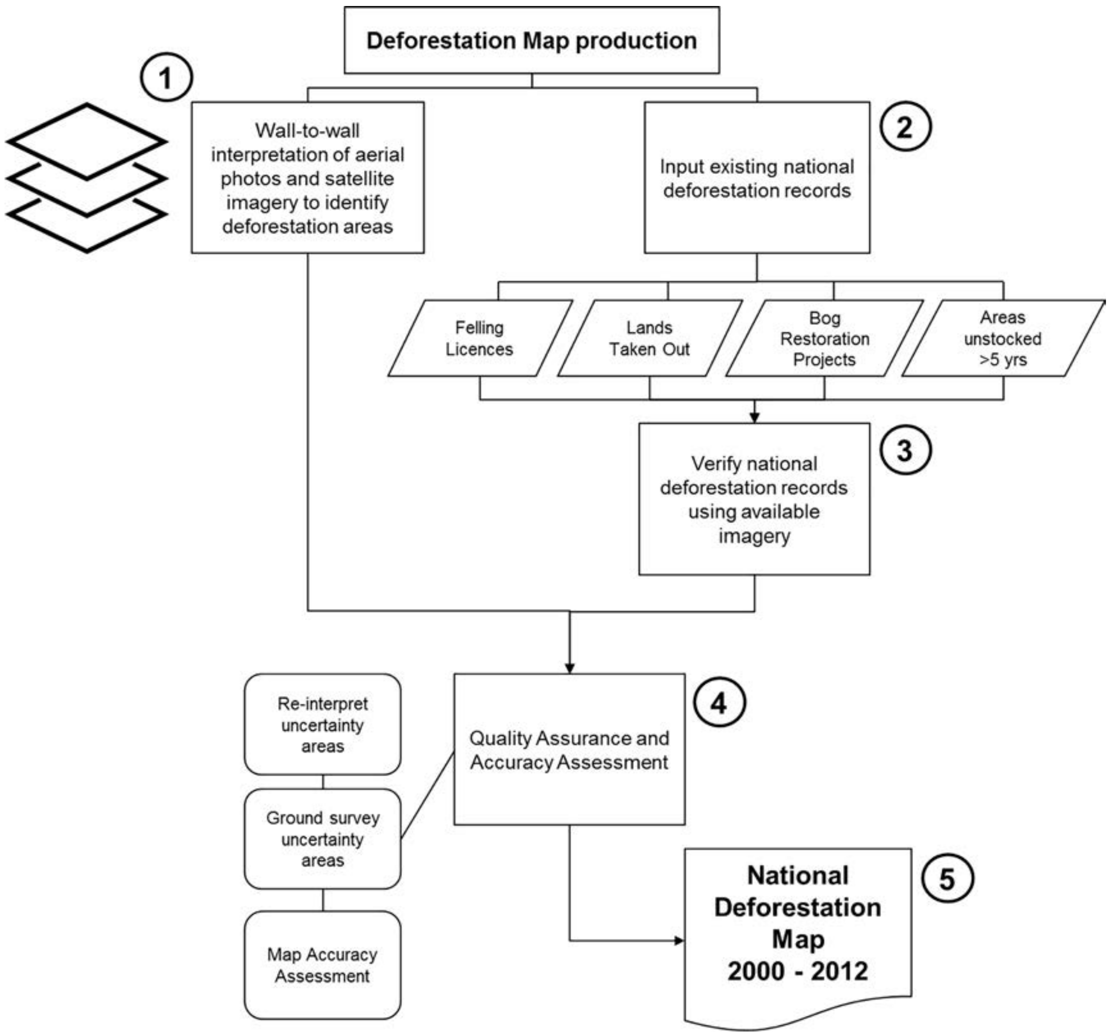

Figure 2.1. Deforestation Map flow chart. Wall-to-wall interpretation of imagery for Ireland was carried out (1), followed by integration of existing national deforestation datasets (2), which were verified by referencing contemporary imagery (3). Quality assurance and map accuracy assessment (4) was carried out (see Chapter 3) before the Deforestation Map was finalised (5).

Throughout this report, the forest definition used for UNFCCC reporting in Ireland was applied, namely, 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). The national forest definition has a legal basis in the Forest Act 2014 (Government of Ireland, 2014).

Wall-to-wall visual photointerpretation of high-resolution imagery was carried out for the entire land mass of Ireland. Three series of ortho-rectified Ordance Survey of Ireland (OSi) aerial photography were available: OSi 2000, 2005 (captured 2004–2006) and 2010 orthophotos at a scale of 1 : 40,000 and pixel size of 1 m. High-resolution (<1 m) imagery (captured between 2011 and 2013) was obtained through the Bing Maps base layer function in ArcGIS 10.2 and used as a reference for 2012. On a county by county basis, the Fishnet tool in ArcGIS 10.2 was used to create a grid of 2 × 2 km photointerpretation sampling units (photo-plots) in each county (Figure 2.2). In total, 18,889 photo-plots were interpreted at a scale of 1 : 8500. A time-series visual assessment of orthorectified 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 (see Figure 2.3 for examples). Two existing forest vector datasets were used to aid interpretation: (1) the most recent Forest Service national forest cover map (Forestry2012), 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 were recorded, including forest type, age, ownership, LUT and extent (i.e. whether the forest was partially or completely removed). Categories of forest type were conifer, broadleaf and mixed. 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. Private grant-aided forests are defined as privately owned afforested land in receipt of either grant and/or premium payments (1980 onwards), while private non-grant aided refers to the remaining privately owned plantations or semi-natural forests. The term “state established” was applied to forests that were planted by the state but which may have been sold into private ownership prior to deforestation activity. Recording of LUTs was based on UNFCCC land-use reporting

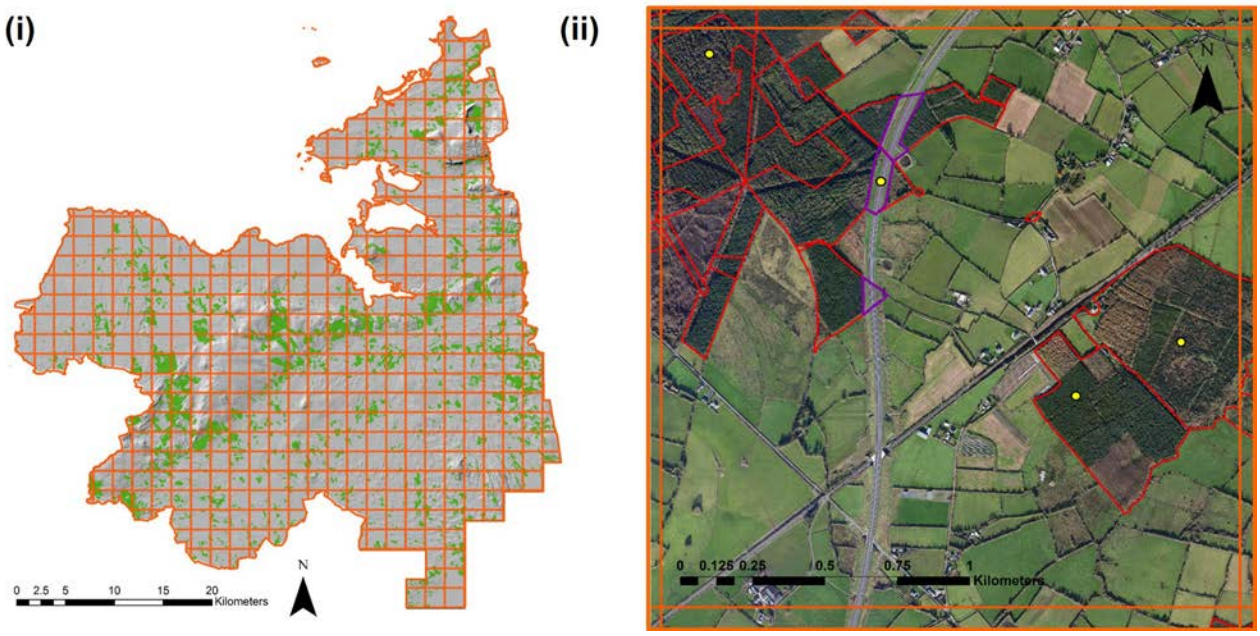

Figure 2.2. Example of fishnet grid (i) and 2 × 2 km photo-plot (ii) used to identify deforestation events. The Forestry2012 vector dataset (shown in red) was used to aid interpretation. Deforestation events were digitised (shown in purple) and a suite of attributes were recorded. Independent accuracy assessment points are shown in yellow. Imagery source: DigitalGlobe, GeoEye, Microsoft, CNES/Airbus D (via ArcGIS Online Basemap Imagery).

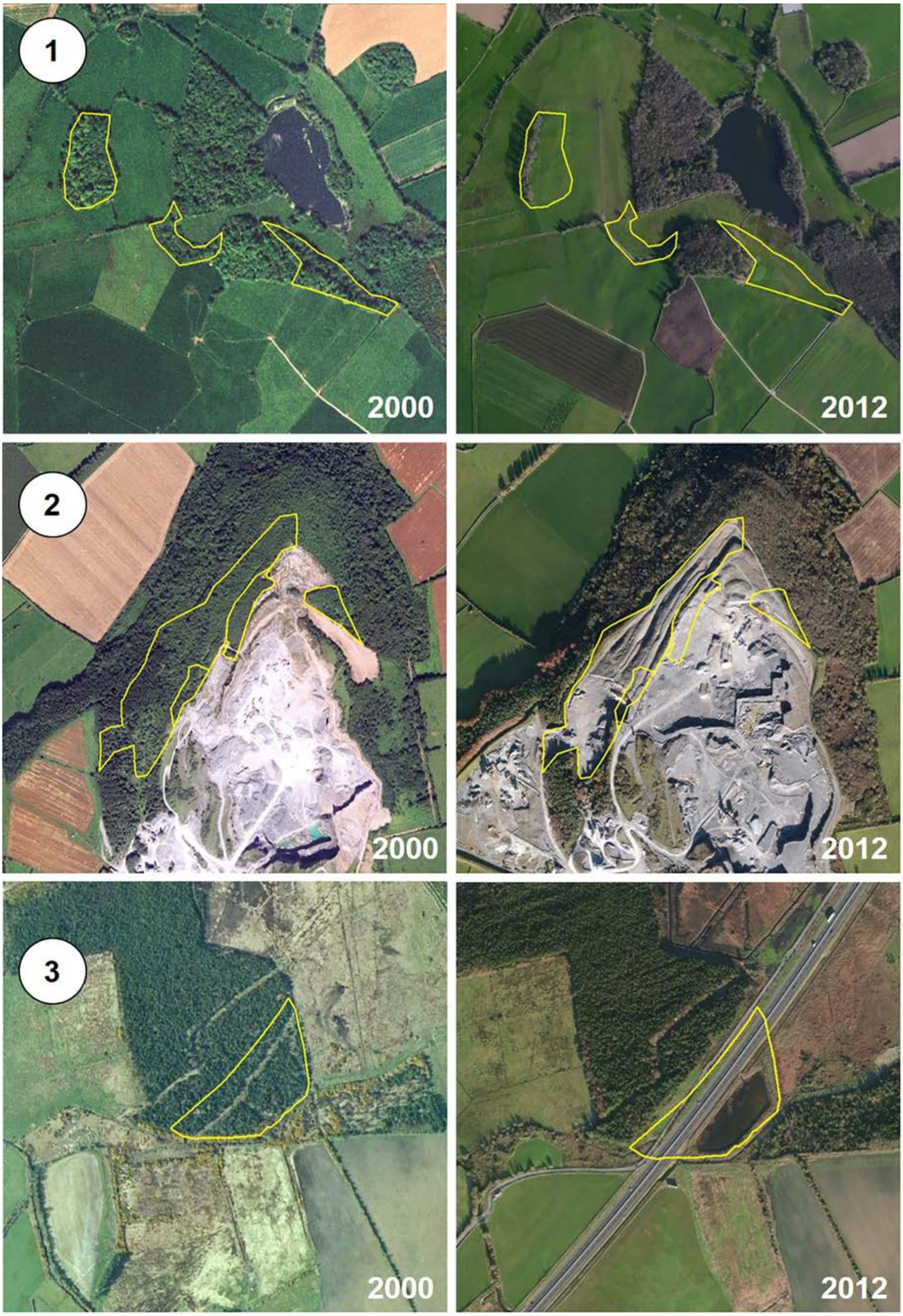

Figure 2.3. Examples of contemporary deforestation events: (1) the conversion of broadleaf woodland to agricultural grassland; (2) the removal of young forest for quarrying; and (3) road construction on afforested land. OSi aerial imagery is reproduced under Licence No. EN 0076414.

categories, namely forest, settlement, grassland, cropland, wetland and other land (see the glossary for definitions). Where appropriate, pre-existing sources of deforestation area information for the study period were incorporated into the Deforestation Map dataset. In Ireland, land owners are legally required under the Forestry Act 1946 to obtain consent for the majority of deforestation activities in the form of Limited Felling Licences (LFLs). Maintained by the Forest Service, LFL records contain information regarding the area and location of deforested land. Afforested areas less than 10 years old are exempt from LFL requirements. However, if the area is in receipt of premium payments, forest owners are obliged to notify the Forest Service if these areas are removed from forest land use. Since 2007, records of lands taken out (known as LTOs) of forest land use are maintained by the Forest Service. Deforestation areas indicated in LFL and LTO hard copy applications were verified by referencing aerial photography. If deforestation areas in LFL and LTO records were not already captured in the photointerpretation process, they were digitised and added to the Deforestation Map geodatabase.

From 2002 to 2008, Coillte Teoranta (state forestry company) and various other agencies undertook large-scale active raised and blanket bog habitat restoration projects under the European Union (EU) LIFE funding mechanism. Spatial information on restoration activities in the study regions involving the conversion of forest land use to bog land use was obtained from Coillte Teoranta and used to supplement deforestation identification. Additional information on forests potentially remaining unplanted after clear-felling for more than 5 years was obtained through the Forestry2012 dataset. Using land-cover attributes in Forestry2012, areas listed as forest in 2000, clear-felled in 2005, and remaining clear-felled in 2010 and 2012 were extracted. As a result of difficulties in differentiating clear-felled areas from recently replanted forest using imagery alone, all these areas were ground surveyed to verify current land use. Periodic updates to the Forest Service national forest cover map (Forestry2012) 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 were absent in Forestry2012. These areas were examined using imagery to verify deforestation activity and were digitised and added to the Deforestation Map geodatabase if not already captured in the photointerpretation process.

2.2.1 Map quality assurance

In cases where the occurrence of deforestation or associated LUT was uncertain, polygons were reviewed by other expert photointerpreters. Where uncertainty remained following re-interpretation, ground surveys were carried out to verify the extent and nature of the deforestation event. In total, 315 sites were ground surveyed (Figure 2.4). Following field inspection, 67% of these sites were confirmed as deforestation. Sites that were determined not to have been deforested following field inspection included areas that had recently been replanted or which had met the forest definition as a result of natural colonisation of trees subsequent to tree-felling activities. To test the accuracy of assigned attributes in the Deforestation Map geodatabase, a stratified random sample of deforestation polygons ($n = 100$) was selected and information such as forest age, type and land-use transition was cross-checked by an independent analyst to determine percentage agreement. Overall, percentage agreement varied from 80% for the forest age category to 96% for the forest ownership category. A map accuracy assessment and deforestation area error adjustment was carried out and is detailed in Chapter 3 of this report.

2.3 Results

A total of 5457.1 ha of land deforested during the 2000–2012 period was explicitly identified (Table 2.1). Following an accuracy assessment procedure that takes into account potential map errors of omission and commission, an error-adjusted national deforestation estimate of 7465.63 ha (± 785.67 ha) was derived. The process used to determine the error-adjusted deforestation estimate with associated 95% confidence intervals is outlined in detail in Chapter 3 of this report. For the remainder of this chapter, the spatial and temporal distribution of the 5457.1 ha of deforested land explicitly identified in the Deforestation Map is discussed.

The final "Deforestation Map" is shown in Figure 2.5. In total, 3022 deforestation events were detected during the 2000–2012 study period. In general,

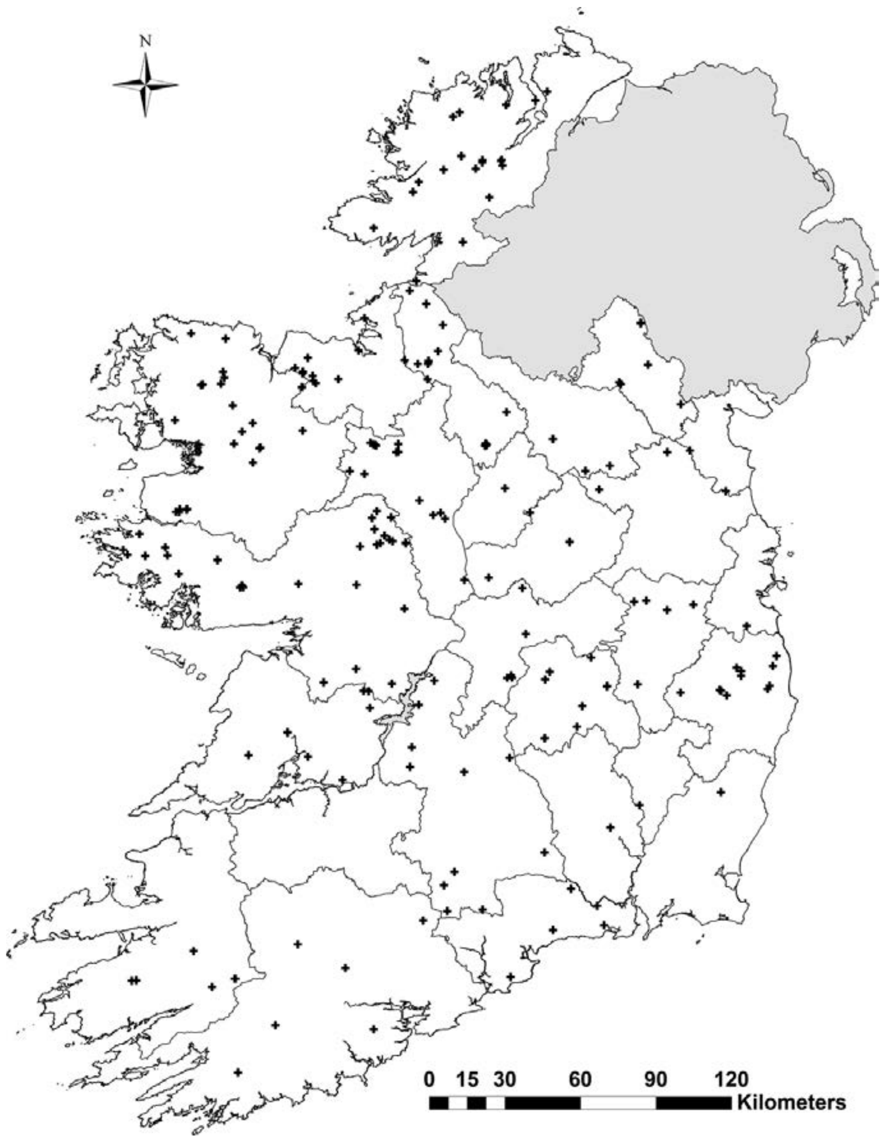

Figure 2.4. Spatial distribution of 315 ground survey sites used to validate deforestation activities.

deforestation events were evenly distributed across the Irish landscape. The counties with the highest total area of deforestation for the period were Counties Galway (1008.5 ha) and Mayo (809.1 ha), having approximately twice the area of deforested land in comparison with the next highest county (Cork; 443.1 ha) (Table 2.1). Counties Longford (28.6 ha) and Dublin (31.9 ha) had the lowest total deforestation area. Relative to the existing area of forest in the county, Counties Monaghan and Louth had the highest level of deforestation, with gross annual deforestation rates of 0.248% and 0.243%, respectively. In contrast, Counties Limerick and Longford had a gross annual deforestation rate of only 0.022% and 0.029%, respectively (Table 2.1). The national gross annual deforestation rate for Ireland for the 2000–2012 period was 0.075%. The average size of deforestation event was 1.81 ha; however, this varied widely between counties. For example, the mean size of deforestation event in County Mayo was 3.97 ha, whereas in County Longford the mean size of deforestation event was only 0.73 ha (Table 2.1). Nationally, the median size of a deforestation event was only 0.59 ha, highlighting the fine-scale character of these events. Figure 2.6 displays the gross annual deforestation rate throughout the country on a 5 × 5 km grid. Based on this map, some clusters of high deforestation areas are visible, most notably central County Clare and the Louth–Monaghan border region.

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

Table 2.1. Details of deforestation area (ha yr⁻¹), rate (%) and mean size of event (ha) in Ireland for the period 2000–2012 per county

County	Deforestation area (ha) Total	2000–2005 (ha yr^{-1})	2005–2010 (ha yr^{-1})	2010–2012 (ha yr^{-1})	Gross annual rate (%)	Mean area of event (ha)
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	1008.5	75.2	121.6	12.3	0.141	3.63
Total/ average	**5457.1**	**415.5**	**565.6**	**350.9**	**0.075**	**1.81**

(350.9 ha yr^{-1}). Again, wide variation between counties was evident (Figure 2.7). In County Monaghan, for example, the opposite trend was apparent, with deforestation decreasing from 20.3 ha yr^{-1} in the 2000–2005 period to 5.2 ha yr^{-1} in the 2005–2010 period and increasing again to 19.4 ha yr^{-1} in the 2010–2012 period (Table 2.1).

For each deforestation event, post-deforestation LUT, based on UNFCCC land-use categories, was determined based on imagery interpretation and/or ground survey. LUTs were principal to settlement, grassland and wetland, although marked temporal and regional variations were evident. In terms of total area, forest to settlement accounted for 38.9% of the total deforestation area (Figure 2.8). Settlement included all built land including windfarms, roads, recreational green spaces and quarries. Examples of forest to settlement conversions also include housing developments, water treatment works and landfill sites. On a national scale, conversion of forest to settlement remained relatively stable during the 2000–2005 and the 2005–2010 periods (approximately 200 ha yr^{-1}), but decreased sharply for the 2010–2012 period (78.45 ha yr^{-1}). The area of forest–grassland conversions increased in consecutive periods, from 123.1 ha yr^{-1} during 2000–2005 to 144.4 ha yr^{-1} in 2005–2010 and 150.3 ha yr^{-1} in 2010–2012. For Counties Donegal, Galway, Mayo and Sligo, forest–wetland transitions represented the largest proportional area, accounting for 41% of total

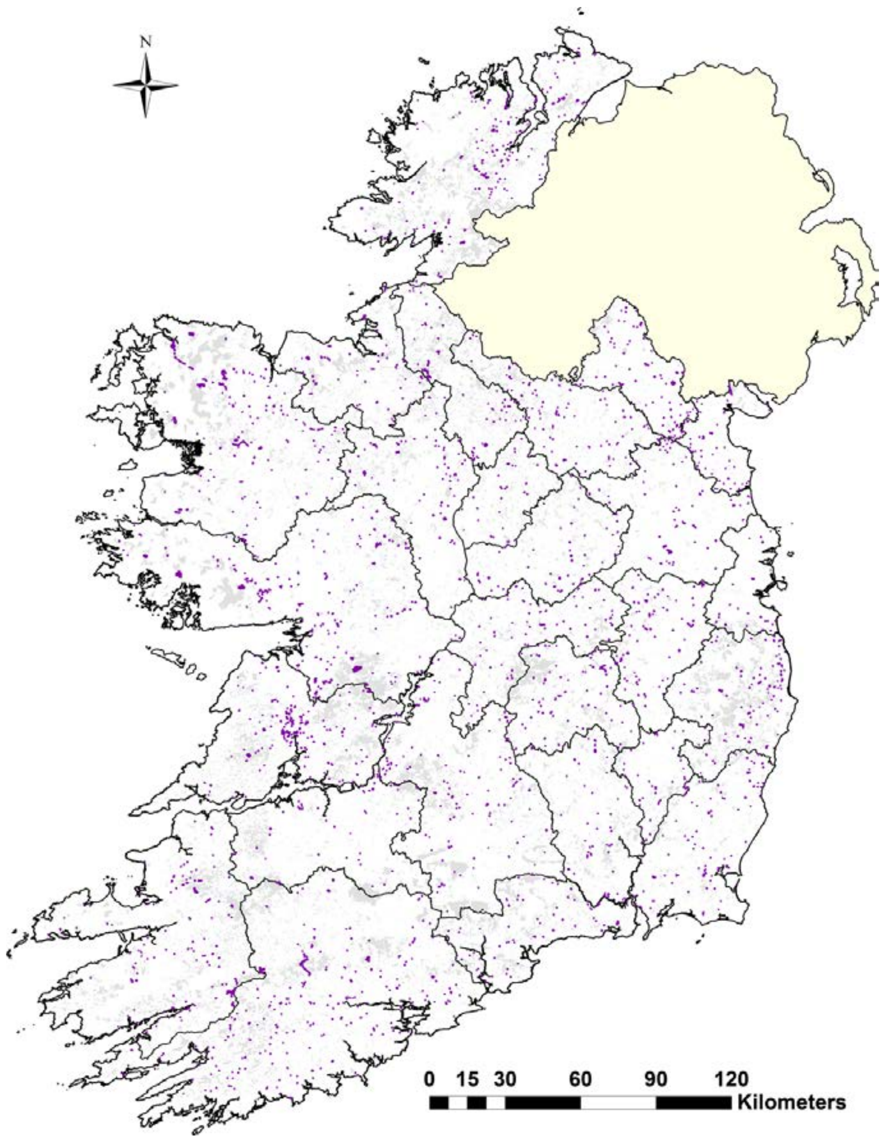

Figure 2.5. The national Deforestation Map for the period 2000–2012 with deforestation areas in purple (actual size slightly exaggerated to increase visibility) and forest cover extent in light grey.

deforestation. Of the total, 36% (783.96 ha) of the deforestation area in these counties was attributable to bog habitat restoration activities, carried out in the mid-2000s. Conversions from forest to other land was 8.9%, consisting mostly of previously forested areas remaining unstocked for > 5 years. Conversion of forest to cropland was negligible, accounting for only 0.2% of the total deforestation area (Figure 2.8). Forests were generally partially removed during a deforestation event, with only 11% of events involving the complete removal of a continuous forest parcel.

The rate of deforestation in forest type, age and ownership categories was also recorded based on ancillary data, ground survey and image interpretation. Despite decreasing in consecutive periods, the gross annual deforestation rate was greater in broadleaf-dominated forests in comparison with mixed and conifer forests (Figure 2.9). The rate of deforestation of conifer and mixed forests increased from 2000–2005 to 2005–2010, but decreased for the 2010–2012 period. For conifer-dominated forests, deforestation rate was highest in the 20–40 years category. In mixed and broadleaf-dominated forests, gross annual deforestation rate increased with forest age. Almost half of the total deforested area during 2000–2012 occurred in state-established forests (2757.2 ha), with the majority of this taking place in conifer-dominated forests. Only 27.7 ha of state-established broadleaf-dominated forest was deforested during the study period. A total of 1122.5 ha of deforestation occurred in privately owned forests in receipt of some form of grant

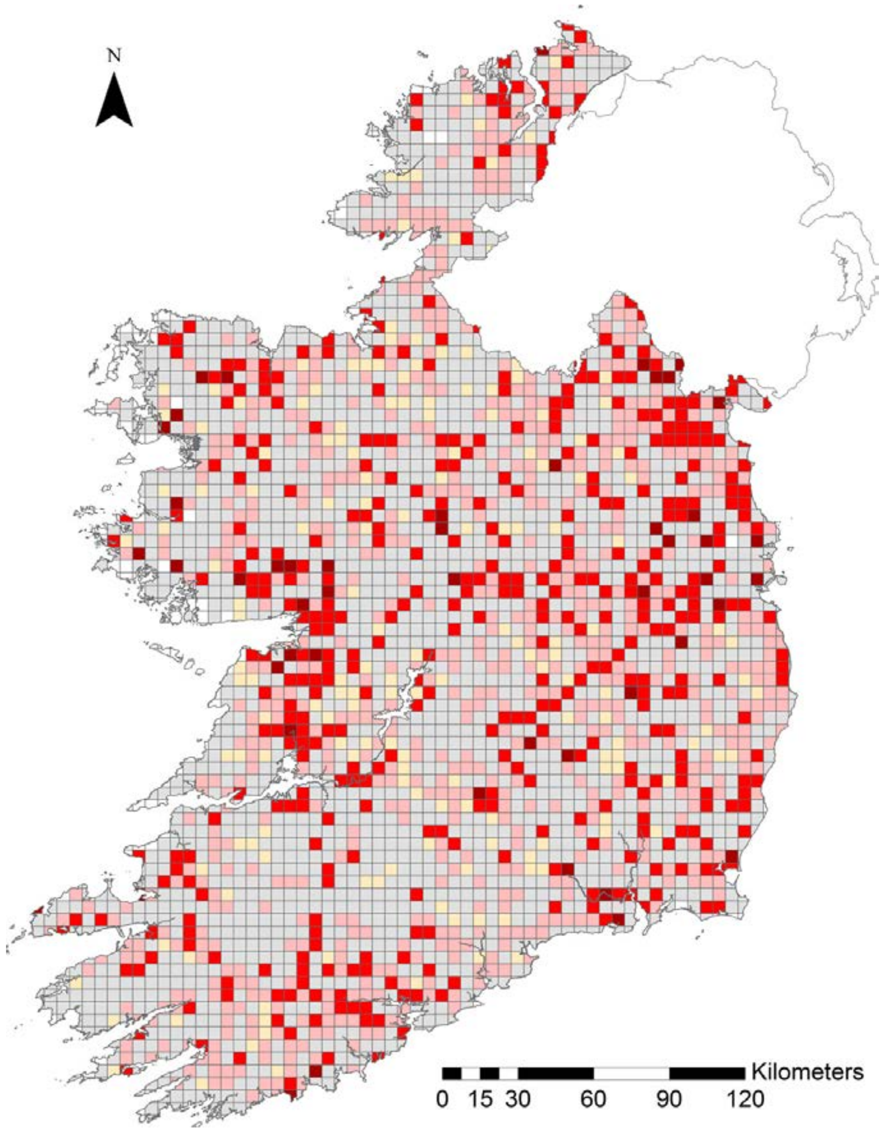

Figure 2.6. The gross annual deforestation rate on a 5 × 5 km grid. White squares indicate no forest, grey squares indicate forest but no deforestation, beige squares indicate a gross annual deforestation rate of < 0.01%, pale red squares indicate a gross annual deforestation rate of 0.01%–0.1%, red squares indicate a gross annual deforestation rate of 0.1%–1%, and dark red squares indicate a gross annual deforestation rate of > 1%.

aid. Within this, 730.7 ha occurred in conifer-dominated forests, 229 ha in broadleaf-dominated forests and 162.8 ha in mixed forests. During the study period, 1566.9 ha of deforestation took place on privately owned non-grant aided forests, the majority of this occurring in broadleaf-dominated forests (1284.5 ha) (Figure 2.9).

2.4 Discussion

The forest area of Ireland continues to expand rapidly, with 137,054 ha of land afforested between 2000 and 2014. Nevertheless, some previous evidence suggests that the gross national deforestation rate in Ireland is also increasing. This study represents the first national-scale, spatially explicit assessment of 21st century deforestation in Ireland. Despite regional variations, no consistent long-term trend of increasing deforestation was recorded. An increase in the gross annual rate of deforestation was recorded from the 2000–2005 period to the 2005–2010 period; however, this was followed by a decrease in deforestation in the 2010–2012 period. Overall, the cumulative deforestation area in 2000–2012 was negligible in comparison with the cumulative afforestation area for the same period (Figure 2.10). The 2000–2012

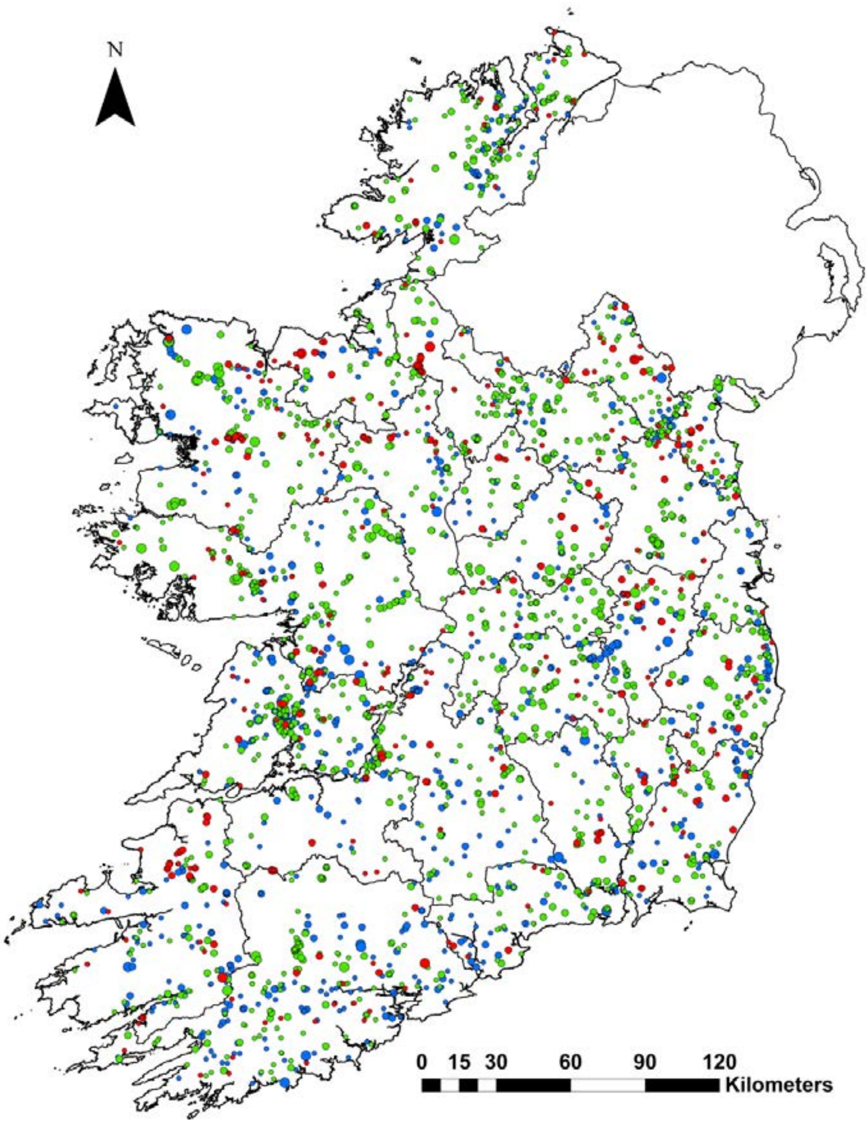

Figure 2.7. Spatial and temporal distribution of deforestation events 2000–2012. Blue points represent deforestation events 2000–2005, green points represent deforestation events 2005–2010 and red points represent deforestation events 2010–2012. The size of the point is relative to the size of the deforestation event. Smallest points are representative of deforestation events < 1 ha in size, medium-sized points are representative of deforestation events between 1 ha and 10 ha in size and largest points are representative of deforestation events > 10 ha in size.

deforestation rate in Ireland (0.075% yr^{-1}) was less than current rates of deforestation in other European countries with similar forest cover areas, such as Belgium (0.22% yr^{-1}), the Netherlands (0.13% yr^{-1}) and Switzerland (0.3% yr^{-1}) (FAO, 2015).

The increase in deforestation area between 2000–2005 and 2005–2010 is probably related to large-scale bog restoration programmes, carried out by Coillte Teoranta and other agencies. Active raised and blanket bog habitat restoration activities included the clear-felling of forested areas and conversion to their pre-afforestation land use of bog/heath. Although some felling operations took place pre-2005, an increase in forest to bog conversions occurred in the 2005–2010 period. These restoration programmes have a significant influence on the overall findings of the study, particularly for attributes such as average size of deforestation event and deforested land ownership. Compared with 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

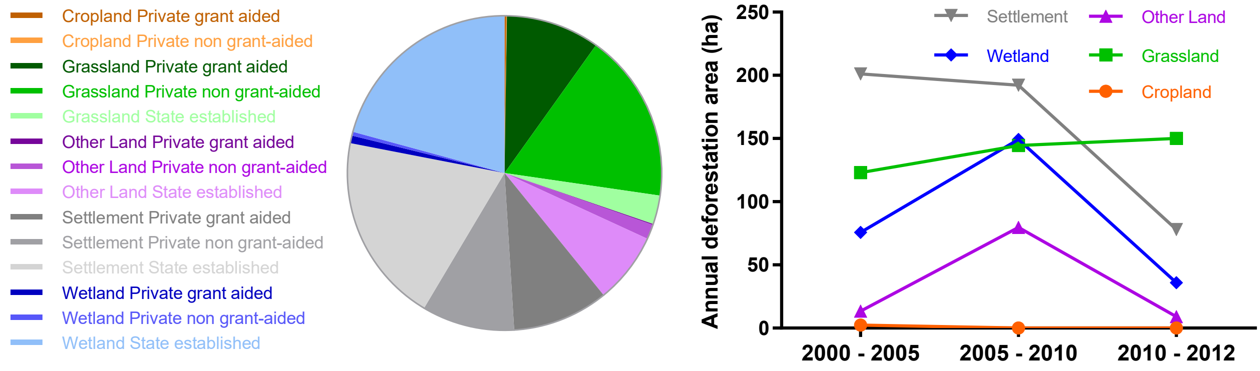

Figure 2.8. Proportional area of post-deforestation land-use transitions by ownership categories (left) and (right) total annual deforestation area for post-deforestation land-use transitions for three periods (2000–2005, 2005–2010, 2010–2012).

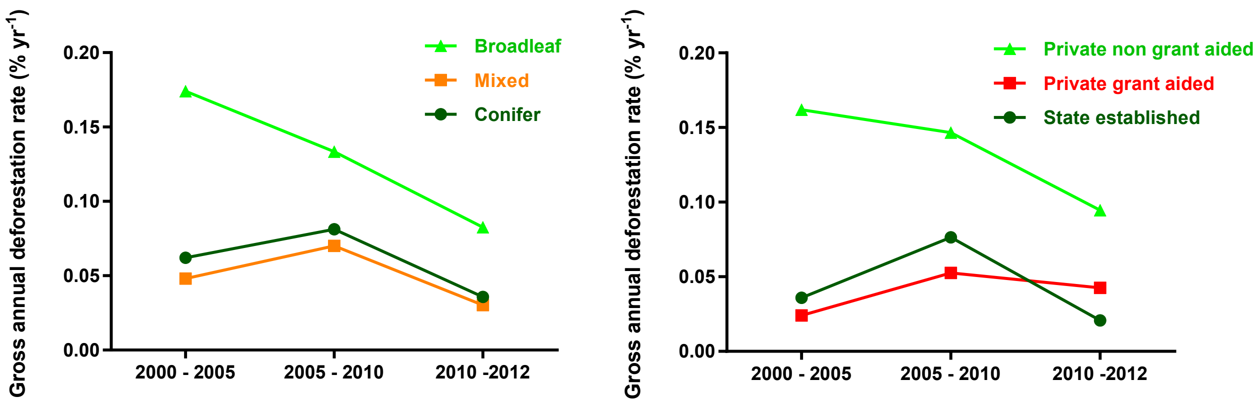

Figure 2.9. Gross annual deforestation rate of (left) different forest types (broadleaf, conifer and mixed) and (right) ownership categories (state established, private grant aided and private non-grant aided).

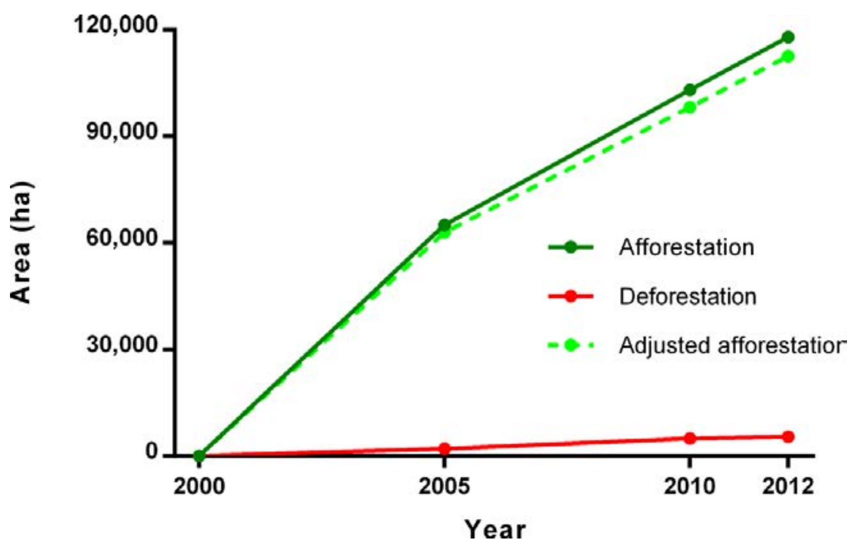

Figure 2.10. Cumulative afforestation (dark green), deforestation (red) and adjusted afforestation (dashed green line) area (ha) in Ireland for the period 2000–2012.

events from 1.81 ha to 1.51 ha. Similarly, omitting bog restoration areas from the analysis would reduce the proportion of "state-established" forests from 50% to 34% of the total deforestation area. It is possible that more deforestation for environmental and conservation management purposes may be carried out in the future, including the potential premature felling of commercial forests to provide suitable habitat for threatened species such as the hen harrier (*Circus cyaneus*).

An increase in conversions from forest to settlement also occurred from the 2000–2005 period to the 2005–2010 period, followed by a sharp decline in the 2010–2012 period. Between 2000 and 2007, 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 decline in the construction sector post 2008 (Whyte *et al*., 2013), which is reflected in a reduction in the conversion of forest land to settlement for the same period.

Few forest conversions to cropland were identified throughout the country. In comparison with other UNFCCC land-use categories such as grassland and wetland, cropland is relatively infrequent, accounting for 5% of the total land area (Forest Service, 2013). Cropland is largely associated with productive agricultural land and is generally not considered to be a competing land use with forest in Ireland, and therefore the lack of deforestation conversions to cropland is unsurprising.

A high inter-county variability in deforestation rate was evident in the study, indicating changing spatial and temporal pressures on forest land use. In County Donegal, 50% of the total deforestation area was attributable to conversions to settlement, with 18% attributable to forest–grassland LUTs. In contrast, in County Clare, only 34% of deforestation was associated with conversion to settlement with forest–grassland being the principal LUT (48%). Regional clusters of deforestation activities were also evident, such as areas surrounding Ennis, County Clare, and on the Louth–Monaghan border. In general, deforestation activities in both these areas principally involved the conversion of forest land to agricultural 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 availability of a national geodatabase of deforestation activities facilitates the examination of regional influences on forest-related land-use change events. Further research is required to investigate the regional drivers of deforestation and develop tools that may predict future deforestation hot spots.

The rate of deforestation of broadleaf forests was considerably higher than for mixed and conifer-dominated forests. Broadleaf-dominated forests constitute only 25% of the national forest area. Indeed, semi-natural broadleaf forests are rare in the Irish landscape, accounting for just 2% of the national forest area (Perrin *et al*., 2008). From a conservation prospective, the high rate of deforestation of broadleaf forests is of concern, particularly in the context of habitat protection legislation such as the EU Habitats Directive (92/43/EEC). Additional analysis indicated that, between 2000 and 2012, 52 deforestation events took place in ancient or long-established woodland, a particular rarity among Ireland's forest types (Perrin and Daly, 2010).

Sixty per cent of deforested non-grant-aided privately owned broadleaf forests were converted to grassland. Anecdotal evidence suggests that changes in the EU Single Farm Payment subsidies have led to an increase in the conversion of broadleaf forest to agricultural land in recent times. However, these changes in the Single Farm Payment came into force in 2013, after the period under investigation in this study, indicating a pre-existing high proportion of broadleaf forest to agriculture deforestation activities. However, empirical evidence linking policy changes with direct land-use conversions is lacking.

3 A Comparison of Deforestation Estimates for Ireland 2000–2012 Using Different Approaches

3.1 Introduction

A number of disparate datasets containing information on 21st century deforestation activities in Ireland currently exist. For example, re-sampling of NFI permanent plots is the principal source of deforestation information for Ireland's NIR on GHG emissions to the UNFCCC. The large uncertainty associated with Ireland's NFI deforestation estimates is due to the low proportion of deforestation plots in relation to the total number of forest plots (0.8–1.3%) (Forest Service, 2007). In the context of ongoing national reporting, a key question is whether or not the true extent of deforestation area falls within the large confidence intervals associated with NFI-derived deforestation estimates. Another constraint of NFI-derived deforestation estimates is that such a sample-based methodology can be applied only on a national scale and is therefore not useful for monitoring change on a regional or local scale.

The primary source of annual information on deforestation events in Ireland comes from limited felling licence records. In Ireland, the Forestry Act 1946 legally requires land owners to obtain consent for the majority of deforestation activities in the form of LFLs, which are maintained by the Forest Service. However, it is recognised that felling licence deforestation estimates are incomplete as no unlicensed or exempted deforestation activities are accounted for. For example, the felling of trees by the Electricity Supply Board is exempted from felling licence requirements. Recent studies have identified problems with other land-use change accounting methodologies, including resolution issues associated with the use of CORINE data (e.g. Black *et al*., 2008). Although some of these datasets have been used in the creation of the national Deforestation Map 2000–2012, only deforestation events verified by imagery interpretation and ground survey were included in the final map and geodatabase. Indeed, the thorough evaluation of these datasets during the creation of the Deforestation Map highlighted many erroneous accounts of deforestation activities within.

Yearly updates of national deforestation areas using the Deforestation Map approach described in Chapter 2 of this report may be challenging as a result of the low temporal resolution of imagery and time constraints relating to wall-to-wall manual photointerpretation. Hence, the use of datasets such as the NFI, felling licences and CORINE information may be important in future accounting procedures. Given the outlined limitations, comparison of existing deforestation datasets is required to inform land-use change accounting approaches. Hence, the objectives were twofold: (1) to compare deforestation area estimates and accuracies of three existing Irish deforestation estimation methodologies (NFI, national statistics and CORINE) and the new Deforestation Map; and (2) to compare associated LUTs as estimated by the different approaches.

3.2 Methodology

Deforestation estimates derived from NFI, CORINE Land Cover (CLC) changes, combined national statistics and the new Deforestation Map were compared.

3.2.1 Irish National Forest Inventory

The Irish NFI is a detailed survey of permanent forest sample plots with the purpose of assessing the extent and nature of Ireland's forests. The first Irish NFI was completed in 2007 (Forest Service, 2007). To identify permanent forest sample plots, photointerpretation of 17,423 points was carried out on a randomised systematic 2 × 2 km grid overlaying Ireland. The primary dataset used was ortho-rectified aerial photographs obtained from OSi. The first aerial photointerpretation exercise was carried out in early 2005 using aerial photographs from 2000. Three secondary forest datasets were used: (1) Forest Service grant- and premium-aided forest plantations map, 1990–2006; (2) the Forest Inventory and Planning System (FIPS) (Gallagher *et al*., 2001); and (3) Coillte Teoranta (state forestry company) forest inventory dataset for state-owned forest land. Where forest/non-forest land use remained unclear, ground survey of points was carried out to determine land-use type. In total, 1742 permanent sample forest plots were established for the first NFI. Plots that were clearly forest based on 2000 aerial photos and secondary datasets, and were not forest following ground survey in 2005/2006 and reinterpretation of aerial photos from 2005, were classified as deforestation plots. The NFI second cycle was completed in 2013, with field work being carried out from 2009 to 2012 (Forest Service, 2013). For the second cycle of the NFI, deforestation 2006–2012 was defined as a change in land-use category of a permanent sample plot from forest (first cycle) to non-forest (second cycle) based on ground survey. Based on the sampling design, each forest plot is representative of 400 ha of forest nationally. Hence, each "deforestation" plot represents 400 ha of deforested land. Following Penman *et al*. (2003), the standard error of the NFI deforestation estimate is calculated as:

$$A\sqrt{((pi(1-pi))/(n-1)} \quad (3.1)$$

where p_i is the proportion of deforestation plots to forest plots, A the total forest area and n the total number of sample points. The 95% confidence interval for the deforestation area estimate is given approximately by ±2 times the standard error.

3.2.2 CORINE Land Cover changes 2000–2012

The CORINE data series was established in 1985 by the European Community (EC) as a means of compiling geo-spatial environmental information in a standardised and comparable manner across the European continent. Using a semi-automated approach, pan-European datasets of classified land-cover types are available for 1990 (CLC 1990), 2000 (CLC 2000), 2006 (CLC 2006) and 2012 (CLC 2012). For Ireland, Landsat 5 TM, Landsat 7 ETM, SPOT 4/5 and IRS-P6-LISSIII satellite imagery was used in combination with an ancillary dataset to create a 2000–2012 national land-use/land-cover change dataset (Lydon and Smith, 2014). CORINE uses a hierarchical classification system containing 44 land-cover categories (Feranec *et al*., 2010). For this study, areas changing from forest land-use/land-cover categories (311 broadleaf forest; 312 coniferous forest; 313 mixed forests; 324 transitional woodland scrub) to non-forest land-use/land-cover categories were extracted from the CLC 2000–2006 and CLC 2006–2012 datasets for comparison with NFI, national statistics and the Deforestation Map.

3.2.3 National statistics

The regulation of the felling licences is the responsibility of the Forest Service 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. Under Part IV Section 37(1) of the Forestry Act 1946, "it shall not be lawful for any person to uproot any tree over ten years old or to cut down any tree, unless the owner of the land on which the tree stands has given to the sergeant in charge of the Gárda Síochána station nearest to the tree a notice in writing of intention to uproot or cut down the tree". The 10-year threshold was included in the Act so as not to impede the routine management in nurseries where young trees are uprooted. However this provision in the Act also meant that afforested areas less than 10 years old were exempt from licensing requirements for deforestation activities. Where forest areas less than 10 years old are subject to grant and premium payments under a national afforestation scheme, forest owners are obliged to notify the Forest Service if these areas are removed from forest land use. Since 2007, spatial records of LFLs and LTOs of forest land use have been maintained by the Forest Service. For this study, the spatial extent of all LFL and LTO deforestation areas were digitised in ArcGIS 10.2 based on hard copy maps provided in licence applications. From 2002 to 2008, Coillte Teoranta and various other agencies undertook large-scale active raised and blanket bog habitat restoration projects under the EU LIFE funding mechanism. Spatial information on restoration activities in the study regions involving the conversion of forest land use to wetland land use was obtained from Coillte Teoranta. Finally, supplementary data on forest areas remaining unstocked for > 5 years were also obtained through the Forestry2012 dataset. Using land-cover attributes in Forestry2012, areas listed as forest in 2000, clear-felled in 2005, and which had remained clear-felled in 2010 and 2012 were extracted. As a result of difficulties differentiating clear-felled areas from recently replanted forest using imagery, all these areas were ground surveyed to verify deforestation. LFL, LTO, bog restoration data and temporality unstocked areas were combined and termed "national statistics" for the purposes of this study.

3.2.4 Deforestation estimate accuracy assessment

An independent accuracy assessment of deforestation areas derived from national statistics, CORINE and the Deforestation Map was carried out using imagery point sampling and ground survey plots (it was not possible to carry out a map accuracy assessment for NFI deforestation areas as a result of its sample-based methodology). A previous version of the Irish national forest vector dataset (Forest2000) was used as reference data for forest land-use area for the year 2000. Forest2000 is based on automatic classification and on-screen interpretation of Landsat TM imagery, panchromatic orthophotos and OSi 25inch map series (FIPS98) (Gallagher *et al*., 2001), with an additional 2 years of Forest Service forest premium spatial information. Within Forest2000, 7936 stratified randomly located points were generated in ArcGIS 10.2. The selection of points was restricted to areas listed as forest land use in 2000 and where post-2011 high-resolution imagery was available in Google Earth (>85% of the study area), it was used as a reference for 2012 land use. Points were imported to Google Earth and at each point the underlying pixel and its surrounding pixels (a total of nine pixels) were visually interpreted by five photointerpreters. Only areas where a clear, permanent, non-forest land use was evident in 2012 were recorded as deforestation (i.e. clear-felled areas in post-2011 Google Earth imagery areas were not deemed as deforestation). Independent ground survey points were added to the accuracy assessment dataset. Land Use/Cover Area frame Survey (LUCAS) is a ground-based survey, with direct observations of land use recorded by field surveyors at 270,000 permanent sampling units throughout the EU in 2012. All LUCAS plots occurring within Forest2000 were added to the accuracy assessment dataset ($n = 219$). NFI forest plots ($n = 1845$) plots were ground surveyed in 2004–2006 and again in 2010–2012 to determine current land use. LUCAS, NFI ground survey plots and Google Earth interpretation points were combined into one accuracy assessment reference dataset (total $n = 10{,}000$). Following comparison between each map and the reference dataset, the resulting population error matrix was used to calculate producer's accuracy (the proportion of deforested points based on the reference data that were 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).

3.2.5 Deforestation Map area error adjustment and uncertainty analysis

Mapped change area is likely to differ from actual change area on account of a classification error, even when map accuracies are high. Once a map accuracy assessment has been carried out, an error-adjusted change area and estimate of uncertainty can be derived. As outlined by Olofsson *et al*. (2013), it is good practice for land-use change studies to report the error-adjusted change area and confidence intervals, particularly in relation to LULUCF accounting under the Kyoto Protocol (Penman *et al*., 2003). Following Olofsson *et al*. (2013), the first step in the error adjustment of the Deforestation Map area estimate is to calculate the proportional area mapped as deforestation:

$$W_i = A_{m.i} \div A_{tot} \tag{3.2}$$

where $A_{m.i}$ is the mapped area (subscript m denotes "mapped") of category i, in this case deforestation) and A_{tot} is the total area of the map. Next, the estimated area proportion according to the reference classification for deforestation ($\hat{p}_{.j}$) can be calculated as:

$$\hat{p}_{.j} = \sum_{i=1}^{2} w_i \frac{n_{i1}}{n_i} \tag{3.3}$$

where n_i is the total number of mapped points in category i (deforestation) and n_{i1} is the number of deforestation reference points in each map category (i.e. forest and deforestation). An error-adjusted area of deforestation $\hat{A}_1$ can now be calculated as:

$$\hat{A}_1 = A_{tot} \times \hat{p}_{.j} \tag{3.4}$$

For uncertainty analysis, the standard error of $\hat{p}_{.j}$ is calculated as:

$$S(\hat{p}_{.j}) = \sqrt{\sum_{i=1}^{2} W_i^2 \frac{\frac{n_{ij}}{n_i}\left(1 - \frac{n_{ij}}{n_i}\right)}{n_i - 1}} \tag{3.5}$$

From this, the standard error of the adjusted deforestation area estimate is:

$$S(\hat{A}_1) = A_{tot} \times S(\hat{p}_{.i}) \quad (3.6)$$

Finally, the approximate 95% confidence interval for $\hat{A}_1$ is given as:

$$\hat{A}_1 \pm 2 \times S(\hat{A}_1) \quad (3.7)$$

3.3 Results

Considerable spatial variation in deforestation areas between the different approaches was evident (Figure 3.1). The total area of deforested land based on the Deforestation Map was 5457.1 ha, corresponding to a gross annual deforestation rate of 0.075% (Table 3.1). In comparison, the NFI-derived deforestation estimate for the period 2000–2012 was 15,600 ha (±4931 ha), a gross annual deforestation rate of 0.178%. The gross annual deforestation rate derived from national statistics was markedly lower at 0.026% (2297.67 ha). It should be noted that the national statistics dataset is incomplete, as although pre-2007 data are available via bog restoration and unstocked areas datasets, no spatial information on limited felling licences is available pre-2007. Based on CORINE, the total deforestation area and gross

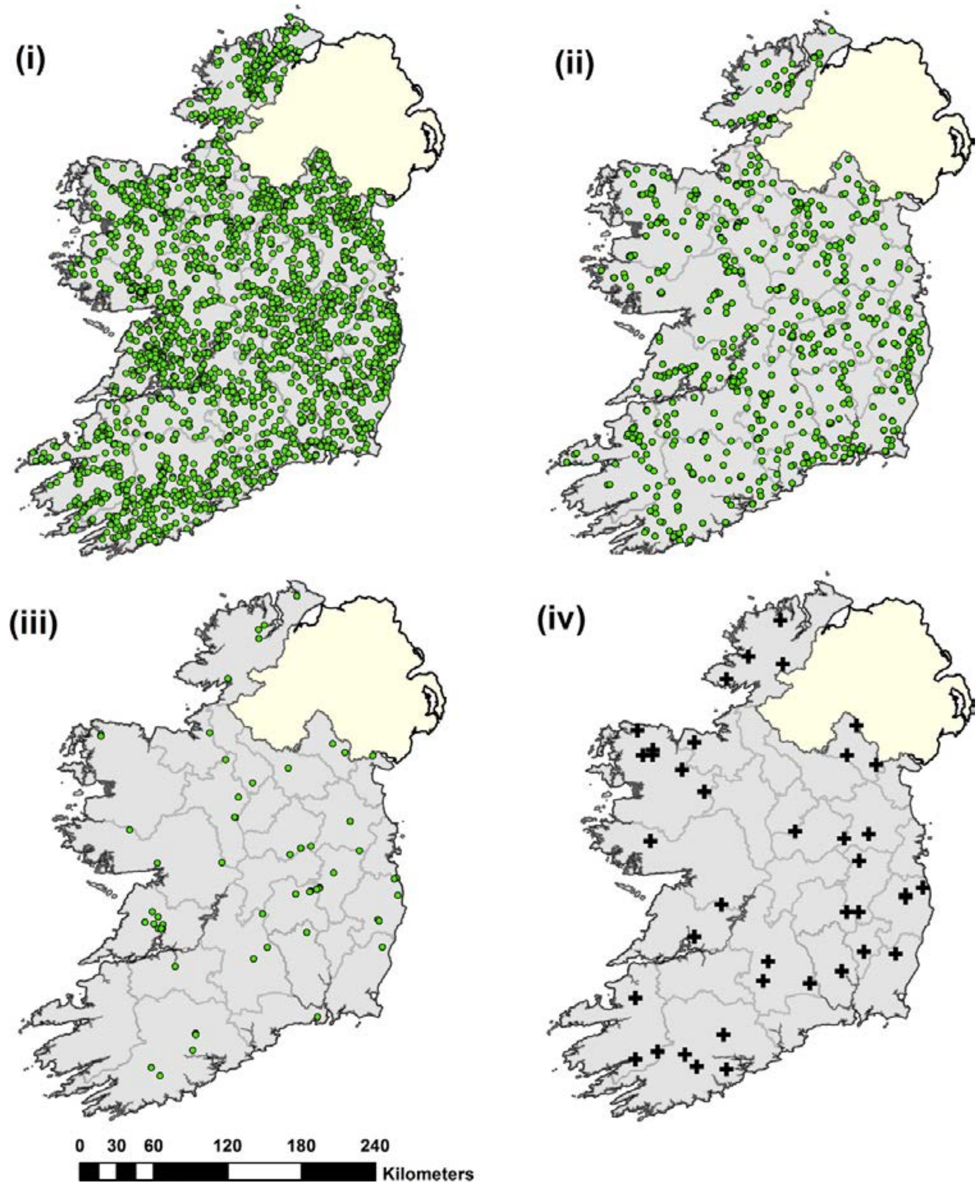

Figure 3.1. The spatial distribution of deforestation events (green dots) derived from (i) the Deforestation Map, (ii) national statistics, (iii) CORINE and (iv) the NFI (black crosses indicate deforested NFI plots 2000–2012).

Table 3.1. Total area (ha), annual rate (% yr⁻¹), number, density and mean size (ha) of deforestation events for the period 2000–2012 based on the Deforestation Map, national statistics, CORINE and the NFI. Also detailed are the results of the map accuracy assessment and error-adjusted deforestation area estimate

Deforestation	Deforestation Map	National statistics	CLC changes	NFI
Area (ha)	5457.1	2297.67	802.2	15,600 (±4931)
Gross annual rate (% yr^{-1})	0.075	0.026	0.009	0.178
No. of events	3022	556	62	39[a]
Mean area of event (ha)	1.8	4.13	12.94	–
Accuracy assessment				
Overall accuracy (%)	99.67	98.95	98.94	–
User's accuracy (%)	97.53	60.61	83.33	–
Producer's accuracy (%)	72.48	18.34	4.59	–
Error-adjusted area estimate	7465.63 ±785.67	–	–	–

[a]Indicates number of NFI permanent sample plots that had a permanent change in land use.

annual deforestation rate were 802.2 ha and 0.009%, respectively. Average size of CORINE-derived deforestation events was 12.94 ha, a six-fold increase on the corresponding value for Deforestation Map-derived estimates, highlighting an underrepresentation of small-scale deforestation events.

Overall accuracies of forest land/deforested land maps were high for the Deforestation Map, national statistics and CORINE (Table 3.1). However, as our study focused on deforestation quantification, user and producer accuracies are of more relevance in determining potential errors of commission and omission. User's accuracy was > 80% for the Deforestation Map and CORINE. In general, loss of forest land use was correctly identified as deforested land based on reference data. For national statistics, user's accuracy was only 60.61%, indicating that many areas classified as deforested actually remained in forest land use. For national statistics- and CORINE-derived maps, producer's accuracy was only 16.51% and 4.59%, respectively, highlighting large omissions of deforested land. For the Deforestation Map, the producer's accuracy was 72.48%, indicating a more accurate quantification of deforestation areas, despite some omissions.

For the Deforestation Map, each post-deforestation LUT was determined based on imagery interpretation and/or ground survey. For the other approaches, post-deforestation LUT as outlined in documentation (e.g. felling licence applications) was recorded and is shown in Figure 3.2. In general, LUTs were to wetland, grassland and settlement, although marked variations between approaches were evident (Figure 3.2).

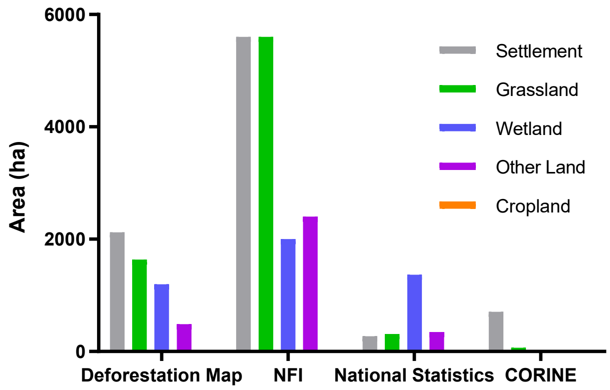

Figure 3.2. Total area (ha) of post-deforestation LUTs 2000–2012 based on the Deforestation Map, NFI, national statistics and CORINE estimates.

Forest–settlement transitions represented the largest proportional deforestation area based on both the Deforestation Map and CORINE-derived estimates, although the magnitude varied greatly (2123.92 ha and 707.93 ha, respectively). In comparison, forest–wetland transitions (1367 ha) constituted the largest proportional deforestation area for the national statistics dataset, with >90% of this attributable to bog habitat restoration activities. The main LUTs recorded following ground survey of NFI permanent sample plots were forest–settlement and forest–grassland. Only the Deforestation Map approach recorded any transitions of forest to cropland, although it was still by far the smallest area of post-deforestation LUT. Interestingly, the Deforestation Map recorded that over 1200 ha of broadleaf forest in non-grant-aided ownership was deforested, principally to agricultural grassland. In comparison, national statistics recorded few conversions of broadleaf forest, only 167 ha across all ownership categories (Figure 3.3).

As it produced the most accurate map of deforestation areas following accuracy assessment, an error-adjusted change area and associated confidence intervals were calculated for the Deforestation Map based on the error matrix. The accuracy assessment revealed significant errors of omission, but few errors of commission, resulting in an error adjustment of total deforestation area from 5457.1 ha to 7465.63 ±785.67 ha.

3.4 Discussion

The clear differences in deforestation area as estimated by the Deforestation Map, national statistics, CORINE and the NFI are not surprising given the methodological differences. Deforestation area based on existing national statistics data alone was greatly reduced in comparison with the Deforestation Map estimates. No spatial information for felling licences is available pre-2007 and hence this dataset is incomplete. Nonetheless, even when the annual rate of licensed deforestation activities is projected for the entire study period and added to the other sources of national deforestation statistics (bog restoration, unstocked areas etc.), the total deforestation area 2000–-2012 would still be just 2709 ha. This is less than 50% of the total area estimated as deforested by the Deforestation Map. National statistics underestimate deforestation area, as unlicensed felling activities are unaccounted for, as indicated by the low producer's accuracy following accuracy assessment (Table 3.1). It is possible that in some cases unlicensed deforestation events recorded contravened felling regulations; however, it was beyond the scope of the study to determine the legality of individual events. In a comparison of deforestation estimates in Britain, Levy and Milne (2004) concluded that deforestation estimates based on felling licences represent a minimum, as unlicensed felling will occur but to an unknown extent. For example, certain deforestation activities do not require a felling licence, including some public infrastructural works. This study highlights the limitations of using felling licence data for deforestation estimation. However, as the only annual record of deforestation activities, such information does provide a valuable indication of trends in the extent and nature of licensed deforestation activities.

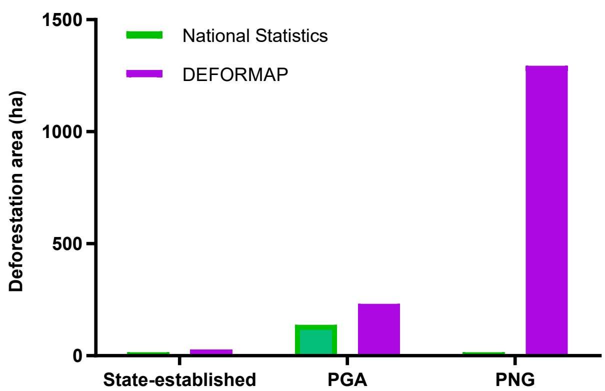

Figure 3.3. Total area of deforestation of broadleaf-dominated forest 2000–2012 in three pre-deforestation ownership categories [state-established, private grant-aided (PGA) and private non-grant-aided (PNG)].

The semi-automated CORINE approach recorded much lower total deforestation areas in comparison with other methods, along with very low producer's accuracies, indicating large omissions of deforested land. This underestimation is probably related to low spatial resolution of CORINE and the size of deforestation events in Ireland. Based on the Deforestation Map, the average size of deforestation event was < 2 ha, with a median size of just 0.7 ha. In contrast, CORINE reported a mean size of deforestation event of 12.94 ha. Given the fine-scale nature of deforestation events in Ireland, the 5 ha resolution of the CLC changes dataset is clearly too large to accurately quantify deforestation areas. A study by Black *et al*. (2008) demonstrated that CORINE data were inappropriate for determining forest-related land-use change events in Ireland because of small land parcel sizes. On account of classification errors and low spatial resolution, other studies have highlighted the limitations of using CORINE data for reporting areas under LULUCF (Cruickshank and Tomlinson, 1996, Hazeu and de Wit, 2004). Higher resolution data products would be more appropriate for monitoring such small-scale events in highly fragmented landscapes with quasi-permanent cloud cover.

The 5457.1 ha of deforested land highlighted by the Deforestation Map is substantially less than the 15,600 ha (± 4931 ha) of deforested land estimated by the NFI for the same period. The magnitude of difference is of significance in the context of UNFCCC reporting. Currently, the post-2000 deforestation area reported in Ireland's NIR is principally based on changes in land use of NFI permanent sample plots. Many countries adopt similar sample-based approaches to estimate deforestation areas (Tomppo *et al*., 2010). However, as outlined previously, in countries where the deforestation rate is low (< 1%), small sample sizes may result in high levels of uncertainty associated with estimates (Magnussen *et al*., 2005, Dymond *et al*., 2008). The benefit of applying a wall-to-wall approach as used in the DEFORMAP project is that a map accuracy assessment can be carried out using standard methods. Accuracy assessment indicated that the error of omission of the Deforestation Map was 27%. Even when an error-adjusted Deforestation Map area (7465.63 ha (± 785.67 ha) is applied, the estimate still falls below the minimum area confidence interval of the NFI estimate, suggesting that NFI-derived data may overestimate the deforestation area.

Given the high accuracies of the Deforestation Map, which combined wall-to-wall photointerpretation, verified national deforestation statistics and ground survey, it is likely that deforestation estimates derived from this method most closely reflect real-world values. Manual interpretation of aerial photography and high-resolution imagery is a cost-effective tool in determining landscape changes (Morgan *et al*., 2010; Ståhl *et al*., 2011). Using only photointerpretation is, however, subject to limitations such as subjectivity of interpretation and length of time required to manually interpret images. The accuracy of photo-interpreted change detection may also be influenced by specific land-use management practices. In Ireland, much of the forested land is managed under a clear-fell replant silvicultural system. In cases where forest cover has been removed, under UNFCCC definitions, clear-felled areas remain in forest land use as long as replanting is carried out within a 5-year period. Omissions of deforested areas using the Deforestation Map approach may have been due to difficulties in distinguishing clear-felled areas from areas unstocked for > 5 years. Thus, it is essential to calculate an error-adjusted area change estimate to account for these omissions. Similar difficulties in identifying long-term unstocked areas pertain to fully automated approaches. Given the nuances of regional land-use changes in Ireland, a combination of Earth observation techniques, national statistics and ground survey is required for quantifying deforestation areas.

4 Radar Remote Sensing for Monitoring Changes in Forest Cover in Ireland: A Preliminary Assessment

4.1 Introduction

To enable sustainable management of forest resources, a common challenge is to quantify spatial and temporal patterns of forest cover (Asner, 2014; Hansen *et al*., 2008; Lynch *et al*., 2013). Recent research has focused on forest cover mapping and change detection on a global scale (Bartholomé and Belward, 2005; Hansen *et al*., 2010, 2013). However, accurate estimation of forest cover and changes on a national level is also required to meet international reporting requirements.

As a Party to the UNFCCC and Kyoto Protocol, Ireland is required to submit annual inventories of forest land-use area and associated changes (UNFCCC, 1992, 1997). A number of estimates for the area of Ireland's forests are available from national and international sources (Table 4.1). Methodologies used to generate these estimates range from sample-based ground measurements to wall-to-wall automatic classification of optical satellite imagery on a pan-European and global scale. While optical remote sensing has been widely used to provide high-resolution maps of forest cover (DeFries *et al*., 2000; Herold *et al*., 2011), its application is limited in countries such as Ireland which have near-constant cloud coverage. On account of their longer wavelengths, electromagnetic waves in the microwave region of the electromagnetic spectrum are not as influenced by atmospheric conditions as sensors operating at optical wavelengths are. Consequently, SAR provides a promising data source for routinely tracking forest changes in Ireland, irrespective of weather conditions. Relatively few applications of SAR to areas such as Ireland with highly sparse and fragmented forest cover have been carried out.

The most common spaceborne microwave remote sensing instruments used for forest applications operate at X- (λ ~3 cm), C- (λ ~5 cm) and L-band (λ ~24 cm). The shorter wavelength (λ) radar (X-band) interacts mainly with the tops of the canopy cover, whereas longer wavelengths (L-band) are able to penetrate further into the canopy. L-band undergoes multiple scattering between the canopy, trunks and soil and is therefore significantly more useful in forest and vegetation studies, as it is able to penetrate deeper into the canopy cover. To date, no assessment of the potential use of L-band radar remote sensing for either forest cover mapping or change detection in Ireland has been carried out. To that end, following the quantification of deforestation areas using a manual approach (i.e. the Deforestation Map), the potential of radar remote sensing for forest cover and change mapping in Ireland was assessed. This preliminary study was carried out for County Longford. Our objectives were (1) to assess the use of L-band SAR data for forest cover mapping in Ireland, and (2) to compare multi-temporal changes in forest cover based on L-band SAR data with deforestation areas as identified in the Deforestation Map.

4.2 Materials and Methods

4.2.1 Study area

County Longford is 1091 km^2 in size and is predominantly lowland, with the north-west of the county consisting of mainly drumlin topography. Forest cover constitutes 7.7% of the total land area. On average, forests in County Longford are 9.54 ha in size, with 71.4% in private ownership. Although non-native conifer species Sitka spruce (*Picea sitchensis*) and Norway spruce (*Picea abies*) are the most common forest tree species (19.4% and 34.3% of the stocked forest area, respectively), native species [principally ash (*Fraxinus excelsior*), birch (*Betula pubescens*) and alder (*Alnus glutinosa*)] are relatively common (36.6% of the forest area).

4.2.2 SAR-derived forest cover maps for County Longford

The Advanced Land Observation Satellite (ALOS) was launched on 19 January 2006 and operated until 12 May 2011. The phased array type L-band synthetic aperture radar (PALSAR) instrument on board of ALOS operated at L-band (λ ~24 cm) and provided

Table 4.1. Available data sources used for comparison of forest cover estimates in Ireland, outlining the potential advantages and disadvantages of each method

Name	Forest definition	Source/method	Spatial resolution	Temporal resolution	Advantages	Disadvantages
Forestry2010	Minimum area of 0.1 ha, trees > 5 m in height and canopy cover ≥ 20% (or with potential to reach those limits)	Irish Forest Service; automatic classification and on-screen interpretation of Landsat TM imagery (1993–1997), aerial photograph interpretation, records of state and private afforestation	< 10 m	Periodic (non-uniform)	High spatial resolution, all newly grant-aided afforested areas accurately captured	Deforestation areas may not be accurately reported, no account of successional forests (e.g. scrub woodland encroachment on abandoned peat)
NFI	Minimum area of 0.1 ha, trees > 5 m in height and canopy cover ≥ 20% (or with potential to reach those limits)	Irish Forest Service; 1827 500 m^2 forest survey plots and aerial photointerpretation, 17,423 grid points	Sample based, 500 m^2 plots	6 years	Fully ground truthed survey plots. Confidence intervals easily calculated from sample	Sample based, not spatially explicit, wide confidence limits on deforestation estimations
JRC Forest Map 2006	Areas occupied by forest with native or exotic trees. Trees are under normal climatic conditions higher than 5 m with a canopy closure of 30%	Joint Research Centre, Italy: supervised classificiation of optical remote sensing data (Landsat ETM+, IRS LISS-III, Spot 4–5, MODIS)	25 m	Periodic (non-uniform)	Pan-European coverage	Low accuracies evident for Ireland – large underrepresentation of forest cover
RADAR Imagery		ESA/Jaxa: ALOS PALSAR fine beam dual (FBD) polarisation	15 m	46 days	High spatial and temporal resolution	Lack of national expertise, national coverage can be expensive
Global Forest Change 2000–2012	Percentage cover of vegetation > 5 m mapped. For this study, areas of tree cover > 20% considered forest	University of Maryland, USA/Google Earth Engine; Time-series analysis of 654,178 Landsat ETM+ images, classified using a decision tree classifier	30 m	Annual[a]	Freely available global data with planned annual updates	Forest area varies widely with national forest statistics, differences in forest definitions

[a]Annual updates have been proposed by Hansen *et al.* (2013).

ALOS, Advanced Land Observation Skills; ESA, European Space Agency; ETM+, Enhanced Thematic Mapper plus; PALSAR, Phased Array type L-band Synthetic Aperture Radar; RADAR, Radio Detection and Ranging.

fully polarimetric capabilities. Two frames (acquired on the same date) were required to obtain complete coverage for the study area. Acquisitions from June 2007, 2008, 2009 and 2010 were acquired via a Category-1 proposal (Cat-1 ID 14194) to the European Space Agency (ESA). Data scenes were speckle filtered using a de Grandi multi-temporal speckle filter and radiometrically and geometrically calibrated and converted to decibels (dB) following Rosenqvist *et al*. (2014). All SAR processing was carried out using SARscape 5.0.001 software within an ENVI 4.8 environment.

A 15 ´ 15 m grid overlaid on the radar datasets was used to extract γ^0 values from the cell centroid locations. A total of 2378 training samples were selected (forest = 1189; non-forest = 1189). These samples were selected on the basis of reference information obtained from ancillary datasets including OSi aerial imagery. The validation followed the widely used *k*-fold cross validation approach (Fielding and Bell, 1997). During the training stage, one of the *k* (in this case *k* = 5) subsets is chosen for validation and the remaining (*k*–1) subsets for training. This process is repeated sequentially until all the datasets have been tested. The classification errors computed from the validation sets are then averaged over the *k*-trials. The *k*-fold cross-validation accuracy is the percentage of validation samples that are correctly classified, and this measure provides a more objective and accurate estimate of classification accuracy than the traditionally used one-fold method.

Two machine-learning algorithms, random forests (RF) and extremely randomised trees (ERT), were applied to the radar backscatter and ancillary (elevation, slope, soils and subsoils) datasets to distinguish between forest and non-forest areas on a per-pixel basis. RF builds an ensemble of individual decision-tree classifiers that are later combined using a majority voting scheme to improve predictive accuracy. For this study, the RF algorithm was run using a 200-tree ensemble and a random sample of predictor variables at each node equal to the square root of the total number of predictor variables.

ERT is a relatively underused (in Earth observation applications) tree-based ensemble classifier. Similar to RF, the number of the trees was set to 200. Finally, small groups of trees and hedgerows that were classified as forest were removed by filtering, as they do not meet the forest definition used in this study. Detailed description of the imagery pre-processing, classification and post-classification filtering procedures is provided in Devaney *et al*. (2015).

4.2.3 Comparison of SAR-derived maps with existing forest cover datasets

Using independent accuracy assessment, a comparative analysis was carried out on radar-derived forest cover maps for 2010 and two national, one pan-European and one global forest cover product.

Forestry2010

Since 1995, the Irish Forest Service has produced spatial datasets detailing the extent of the forest estate in Ireland. Initially known as FIPS, this spatial dataset was derived from automatic classification and on-screen interpretation of Landsat TM imagery (1993–1997), panchromatic orthophotos (1995) and OSi 25-inch map series. Forest boundaries were digitised to within 2 m accuracy of the orthophotos and the OSi 25-inch map series. Since 1998, Forest Service premium and grant-aided forest area information has been added annually to this dataset. For the purposes of this study, all post-2010 afforestation areas were removed from the current dataset, along with any non-forest land-cover areas, to create Forestry2010.

Irish National Forest Inventory

NFI forest cover estimates in the study area were taken from the results of the second NFI, for which field surveys were carried out in 2010–2012. All area estimates for County Longford are taken from the "stocked forest area" statistics of the NFI (Forest Service, 2013).

Forest Map 2006

The Forest Map 2006 is a pan-European forest cover map, produced using an artificial neural network (ANN) applied to optical remote sensing data (Kempeneers *et al*., 2013). Wall-to-wall forest cover data for Europe are available at 25 ´ 25 m pixel size using images acquired during 2005–2007 from the medium-resolution linear imaging self-scanner (LISS-3) sensor on board the Indian Remote Sensing satellite (IRS-P6), Satellite Pour l'Observation de la Terre (SPOT 4/5) and moderate-resolution imaging spectroradiometer (MODIS) imagery. The CLC Map 2006 was used as training data, and LUCAS data and eForest Platform (harmonised NFI data from all EU-27 Member States) were used for its validation. The Forest Map 2006 data covering County Longford was acquired from the EU Joint Research Centre (JRC) at http://forest.jrc.ec.europa.eu/download/data/forest-data-download.

Global Forest Change 2000–2012

In 2013, the findings of a major study on the use of Earth observation (EO) satellite data to map global forest loss and gain from 2000–2012 were published by Hansen *et al*. (2013). A time-series analysis of 654,178 Landsat ETM+ images were classified using a decision-tree classifier to characterise global forest cover and change during the period 2000 to 2012 at a resolution of ~30 m. This data analysis was performed using Google Earth Engine and is available online from: http://earthenginepartners.appspot.com/science-2013-global-forest. For this study, a subset of the global forest cover datasets covering the study area was extracted. The data were re-classified where forest canopy cover ≥ 20% equalled forest and canopy cover < 20% equalled non-forest cover. The global forest cover loss and gain between 2000 and 2012 was added to the 2000 global forest canopy cover product to create a forest cover 2012 product. Finally, forest cover loss during the years 2011 and 2012 was removed to produce a 2010 forest cover dataset for comparison with the other forest cover datasets.

4.2.4 Data harmonisation

The Forest Map 2006 and Global Forest cover products were re-projected into the Irish Transverse Mercator (ITM) projection using a bilinear resampling. For all maps, forest polygons were dissolved to derive a discrete polygon for each continuous forest parcel and the area (ha) of each forest parcel was calculated. Any resulting polygons < 0.1 ha were removed, as they failed to meet the forest definition. As radar coverage was not complete for County Longford, all maps were clipped to a vector boundary layer of areas common to all datasets. From each map, total forest area and average forest size were calculated. Although SAR-derived maps, Global Forest Change (GFC), Forest Map 2006 and NFI-stocked forest areas provide estimates of forest land cover, Forestry2010 is inherently a forest land-use map. Despite the modification of Forestry2010 to exclude non-forest land-use areas, this dataset will include recently clear-felled areas without tree cover and open spaces within the forest.

4.2.5 Accuracy assessment of forest datasets

An independent accuracy assessment was carried out on all forest cover maps. NFI forest plots, LUCAS 2009 and the national survey of native woodlands in Ireland survey plots were combined to create an independent accuracy assessment dataset. Ground visits to all NFI permanent sample forest plots in County Longford were carried out in 2010–2012. The national survey of native woodlands in Ireland was a comprehensive ground survey of native woodlands in Ireland (Perrin *et al*., 2008). A total of 1320 forest plots were surveyed in Ireland during the period 2003–2007. Ground survey forest/non-forest points from County Longford were combined from these sources to create an independent accuracy assessment dataset. The dataset contained 77 forest and 273 non-forest samples. The overall accuracies of forest/non-forest cover maps were calculated using this independent accuracy assessment dataset.

4.2.6. Comparison of multi-temporal SAR forest change maps with the Deforestation Map

The ERT-derived SAR maps of forest loss for 2007–2010 were compared with areas identified as permanent forest loss in the Deforestation Map. Two approaches were adopted. Firstly, the difference in HV backscattering coefficients (γ^0) between image pairs was determined (known as image differencing). A post-classification change detection was also performed whereby classified forest/non-forest maps from each year were compared and any areas moving from forest to non-forest were identified as change. Post-classification change detection is less susceptible to problems encountered at the pixel level (such as shadow and reflection); however, inaccuracies of classified maps will be carried over to the change detection. It should be noted that the SAR-derived change maps do not differentiate forest land cover from forest land use and temporal differences between maps exist as SAR-derived change maps were available only for 2007–2010, whereas the Deforestation Map covers the period 2005–2010. Nonetheless, assessment of these data sources serves as a useful comparison in this pilot study and is intended as a guide for future studies of automated deforestation detection procedures in Ireland.

4.2 Results

The RF and ERT radar classification results for County Longford are summarised in Table 4.2. Overall, accuracies were high (98.1–98.4%), with differences between the two classifiers being minimal. User's accuracy was marginally higher for the forest class than the non-forest class, suggesting a greater tendency of the algorithms to slightly overestimate forest extent (i.e. misclassify non-forest as forest). To assess the influence of the ancillary variables on classification accuracies, the variable importance ranking derived from the RF algorithm was analysed [data not shown, but see Devaney *et al*. (2015)]. Ancillary variables have little contribution to the classification accuracies. Overall, the inclusion of the ancillary data contributes between 2% and 4% to the overall accuracies when considering a forest to non-forest classification approach. The results from this study indicate that, even if ancillary variables are not available, high accuracies can still be obtained using only the radar intensity data.

Table 4.2. Radar classification results

	RF		ERT	
	PA	UA	PA	UA
Forest	0.97	0.99	0.97	0.99
Non-forest	0.99	0.97	0.99	0.97
Overall accuracy (%)	98.10		98.40	
Kappa coefficient	0.96		0.97	

PA, producer's accuracy; UA, user's accuracy.

A comparative analysis of forest area estimates for County Longford for the different forest cover datasets was carried out and is presented in Table 4.3. Considerable variation in the spatial extent of forest cover was found between the sources investigated (see Figures 4.1 and 4.2). Total forest area varied from 11,848.8 ha using ERT-derived estimates to 2153.1 ha using the JRC Forest Map 2006. Mean forest size was highest in SAR-derived estimates (12.51 ha) and lowest in the GFC Map (1 ha). The GFC Map indicated a much larger number of small, fragmented forest parcels than other datasets (Figures 4.1 and 4.2). The highest overall accuracy was recorded for the Forestry2010 dataset: 96.57%. The 5% reduction in user's accuracy for SAR (RF) compared with Forestry2010 indicates that some forest areas were erroneously included in the SAR maps, based on ground-truthed points. However, differences in user accuracies are small relative to the magnitude of difference in forest area derived from SAR (RF) and Forestry2010, potentially due to the limited availability of fully ground-truthed reference plots. Figure 4.3 indicates differences between forest areas in 2007–2010 as identified by (i) SAR-derived post-classification change detection, (ii) image differencing and (iii) areas of permanent loss of forest land use 2005–2010 based on the Deforestation Map. Overall loss in forest cover was much greater for SAR-derived post-classification change maps and image differencing (330.27 ha and 215.61 ha, respectively) compared with deforestation areas in the Deforestation Map (17.64 ha) (Table 4.4). Accounting for temporal differences between maps, the annual rate of forest loss as indicated by post-classification change detection was 1.315% yr^{-1}. Using the image differencing approach, annual rate of forest loss was 0.857% yr^{-1}. When compared with the annual rate of

Table 4.3. Forest area (ha), mean discrete forest parcel size (ha) and accuracy (based on independent accuracy assessment dataset) for forest cover estimation in County Longford based on SAR (RF), SAR (ERT), Forestry2010, NFI, JRC Forest Map 2006 and GFC Map

Source	Forest area (ha)	Mean forest size (ha)	Producer's accuracy (%)	User's accuracy (%)	Overall accuracy (%)
SAR (RF)	10,086.70	13.35	92.21	91.03	96.28
SAR (ERT)	11,848.80	12.51	94.81	89.02	96.28
Forestry2010	7314.60	9.55	88.31	95.77	96.57
NFI	6769.90	–	–	–	–
JRC Forest Map 2006	2153.10	2.26	12.99	90.91	80.57
GFC	8368.50	1	71.43	85.94	91.14

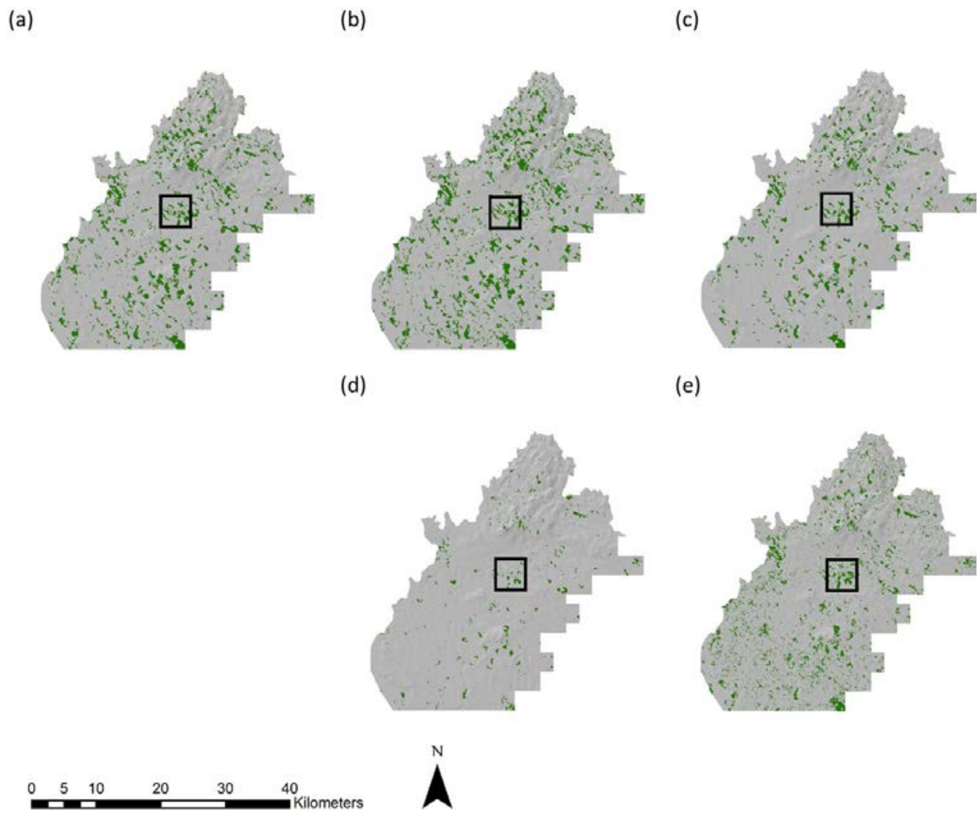

Figure 4.1. The extent of forest cover in County Longford based on (a) SAR (RF), (b) SAR (ERT), (c) Forestry2010, (d) JRC Forest Map 2006 and (e) GFC Map.

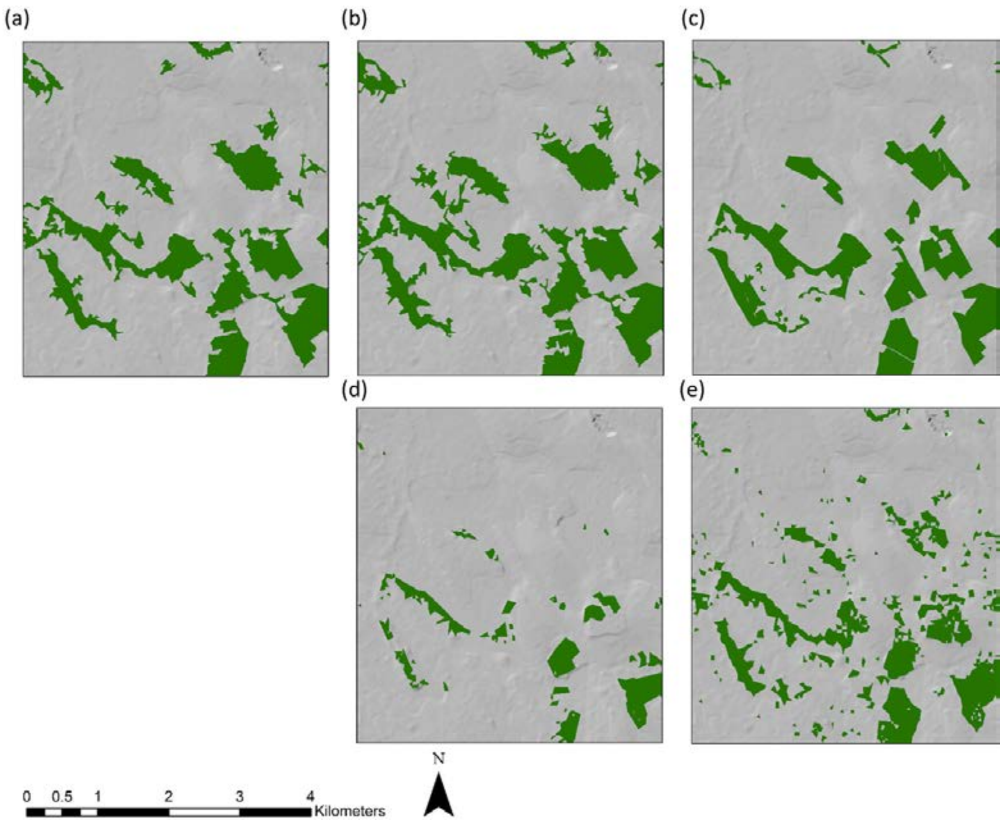

Figure 4.2. Zoomed in (1 : 60,000) extent of forest cover in County Longford based on (a) SAR (RF), (b) SAR (ERT), (c) Forestry2010, (d) JRC Forest Map 2006 and (e) GFC Map.

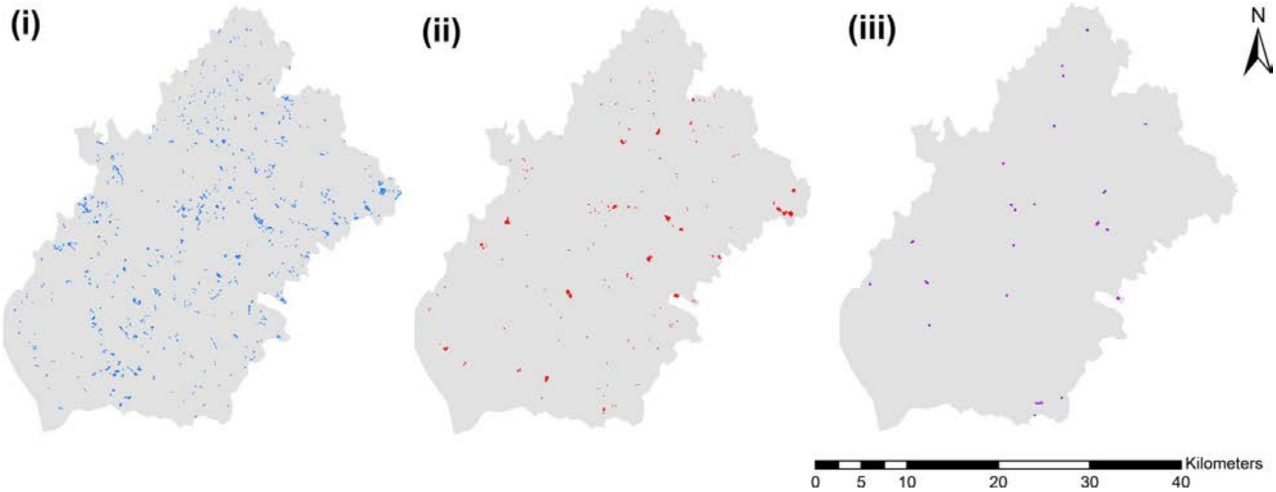

Figure 4.3. Loss in forest cover in County Longford 2007–2010 based on (i) post-classification change detection and (ii) image differencing of multi-temporal SAR imagery in comparison with (iii) deforestation areas 2005–2010 derived from the Deforestation Map.

Table 4.4. Area, annual rate of loss, mean discrete parcel size and total number of forest loss events as identified by SAR-derived post-classification and image differencing maps 2007–2010 for County Longford and comparison with deforestation areas in County Longford in 2005–2010 identified by the Deforestation Map

	Forest loss (ha)	Annual rate (% yr^{-1})	Mean size (ha)	No. events	Overlap with Deforestation Map (ha)
Post-classification changes	330.27	1.315	0.32	1005	2.06
Image differencing	215.61	0.857	1.28	169	1.65
Deforestation Map	17.64	0.042	0.67	26	–

deforestation for the county during the 2005–2010 period (0.042% yr^{-1}), it is clear that the rate of forest *land-cover* loss was much greater than the rate of forest *land-use* loss. The overlapping area between the Deforestation Map and SAR-derived forest cover change maps was low, suggesting that radar maps may not effectively identify permanent change areas; however, temporal differences between the maps means that maps are not fully comparable. Further research is required whereby forest change is identified by sets of aerial imagery and radar imagery from coincident time periods.

4.3 Discussion

For the comparison of forest cover estimates in the study area, observed differences between SAR-derived maps, Forestry2010 and NFI are of particular importance, as these datasets are commonly used in national reporting statistics. For County Longford, the lowest SAR-derived estimate was approximately 40% greater than Forestry2010 and NFI estimates. This discrepancy may be partly explained by changing land-cover trends in the region. County Longford has a high proportion of raised bog land cover, much of which has been used for industrial harvesting of peat for electricity production and domestic heating (Tuohy *et al*., 2009). Anecdotal evidence suggests that, as a result of changing socio-economic circumstances and environmental concerns, industrial practices on many of these peatlands have recently been abandoned, leading to the development of successional woodlands. Within the Forestry2010 dataset, recent, naturally developing forests are not accounted for and hence may be underrepresented. Conversely, SAR-derived maps may have incorrectly identified non-forest scrub vegetation (such as *Ulex* spp.) as forest, leading to an overestimation of the total forest area. These areas support a lower L-band backscatter and could potentially be mapped as a separate class; however, it was beyond the scope of this project.

This study is one of the first to assess the usefulness of the GFC Map for forest monitoring on a regional scale, whereby accuracies are compared with existing and novel national forest cover datasets. Although GFC-derived forest area estimates were within 25% of national (Forestry2010 and NFI) and SAR-derived estimates, overall accuracy was consistently lower in GFC Maps than other sources (with the exception of Forest Map 2006). Visual inspection of forest maps indicates a higher number of small forest parcels in the GFC dataset (Figures 4.1 and 4.2). The possible erroneous inclusion of non-forest areas of tree cover as forest in the GFC dataset may have occurred as a result of difficulties with harmonising forest definitions between the different estimation methodologies. The Irish national forest definition was applied for this study and attempts were made to align all datasets to this definition. Nevertheless, the original GFC dataset was designed to capture percentage cover of all vegetation > 5 m in height, rather than forest as described by the national definition. Although forest cover in Ireland is low compared with other European countries (FAO, 2010), a large area of trees outside forests in the form of hedgerows and scrub exists. The GFC dataset may have incorrectly incorporated some of these areas as forest. No post-classification filtering was carried out on Forest Map 2006 or GFC Forest Maps. However, this process would be unlikely to improve the accuracies of the Forest Map 2006 on account of its large underrepresentation of forest cover, but may influence the accuracies of GFC Forest Maps. Global and pan-continental forest cover maps such as those investigated in this study are essential instruments in the long-term monitoring of large-scale land-cover changes. However, the reduced accuracies of these datasets in comparison with national and the SAR-derived forest maps indicate that caution should be exercised when applying these datasets to nuanced local forest conditions, such as highly sparse and fragmented forest landscapes. Currently, particularly in developed counties where pre-existing forest cover estimation methodologies have been optimally developed for local circumstances, their use for national reporting may be limited.

Of particular note is the possible use of SAR data in the LULUCF sector of UNFCCC inventory reports. SAR-derived forest cover maps for County Longford displayed high accuracies following independent accuracy assessment and were comparable with datasets currently used in national forest reporting. These findings indicate that dual-polarisation radar could aid forest inventories. Although ALOS PALSAR is no longer operational (Rosenqvist *et al*., 2014), a follow-on mission, ALOS-2, was successfully launched on 24 May 2014. Furthermore, continuity of observations will be facilitated by the ever-increasing number of radar sensors being launched. This, in addition to free and open access policies for certain sensor data (e.g. Sentinel-1A/B – launched 3 April 2014), may further constitute a basis for incorporating SAR-derived forest cover estimates into national reporting mechanisms. Although Sentinel-1A/B is not the optimal sensor in terms of technical characteristics for forest mapping/change monitoring, it has the benefit of free and easily accessible data with a high temporal revisit requiring only three scenes for national coverage. The HV band of Sentinel can distinguish between forest and non-forest (similar to the ASAR HV band). A short technical feasibility study on carrying out this analysis on a national scale would be worthwhile.

However, SAR forest mapping is primarily a *land-cover* mapping technique, whereas LULUCF reporting is based on *land use*. In countries such as Ireland where the principal silvicultural method is clear-felling followed by replanting, a change in forest cover is often not associated with a change in land use. Clear-felling is generally associated with a marked change in backscatter signal, but differentiating clear-felling forest management operations from permanent land-use change (i.e. deforestation) may be difficult. For example, this study indicated a much higher rate of loss in forest cover in comparison with areas identified as loss of forest land use. Thus, for reporting land-use change events, the potential use of SAR-based forest cover change identification should be used in combination with data from other sources such as high-resolution aerial imagery, ground surveys and ancillary datasets. In New Zealand, *possible* deforestation areas (> 1 ha) for Kyoto Protocol reporting are first identified by comparing contemporary satellite derived forest cover maps with an existing 1990 land-use map. Next, these *possible* change polygons are checked by expert photointerpreters using reference data to confirm actual deforestation areas and remove areas of spurious change (Dymond *et al*., 2012). In the long term, adopting such an approach may be suitable for deforestation monitoring in Ireland. Firstly, potential deforestation areas would be identified by SAR-derived land-cover change maps. Next, photointerpretation and/or ground survey would be carried out to differentiate forest management operations from permanent loss in forest land use. The availability of a spatial dataset detailing annual clear-felling operations would greatly improve the efficiency of such a process (i.e. clear-felled areas could quickly be removed from the potential deforestation areas dataset). However, in this study, little overlap existed between SAR forest cover loss maps and forest land-use loss in the Deforestation Map, although this may have been due to temporal differences between maps. Further research is required to elucidate the effectiveness of automated satellite-based deforestation detection in Ireland on greater spatial and temporal scales.

5 Conclusions and Recommendations

With increasing national and international reporting obligations, assessing forest-related land-use changes will be a key component of environmental assessment and planning in Ireland. In this study, high-resolution imagery interpretation and novel and existing records of deforestation activities were combined to quantify loss in forest land use in Ireland for the period 2000–2012. This study represents an important development in our understanding of contemporary land-use change in Ireland.

5.1 Future Deforestation Monitoring in Ireland

In the longer term, for the purposes of UNFCCC reporting, yearly updates of national deforestation areas may be challenging using wall-to-wall manual photointerpretation because of low temporal resolution of high-resolution aerial imagery and resource constraints. Nonetheless, the addition of the baseline Deforestation Map dataset would reduce time constraints associated with any future national photointerpretation exercise. Using the DEFORMAP infrastructure, a complete national scale photointerpretation of deforestation areas could be repeated on a cyclical basis should updated national imagery datasets and resources become available. As a result of 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, at present, the application of optical remote sensing is limited in countries such as Ireland which have near-constant cloud coverage. Radar remote sensing systems on the other hand operate in the microwave region of the electromagnetic spectrum and are not as influenced by atmospheric conditions. Consequently, radar remote sensing provides an ideal data source for tracking landscape changes, irrespective of weather conditions or time of day. Based on the findings of this study, 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.

5.2 Recommendations

1. A national-scale photointerpretation of deforestation areas could be repeated on a cyclical basis using updated national imagery datasets. However, until imagery and labour resources become available, or a national semi-automated satellite-based change detection system becomes operational in Ireland, NFI data remains the most accurate source of deforestation area estimates. The deforestation area estimate from the NFI was within 2500 ha of the upper range of the error-adjusted Deforestation Map area estimate for the 2000–2012 period. The findings of the NFI third cycle will reveal more information on spatial and temporal trends of contemporary deforestation in Ireland.
2. This study has highlighted a high level of deforestation in privately owned broadleaf-dominated forests. Indeed, 52 deforestation events between 2000 and 2012 took place in long-established or ancient woodland, which are extremely rare features of the Irish landscape. Further study on this issue is needed to inform policy aimed at reducing deforestation in Irish broadleaf forests.
3. It is possible that some private land owners were not aware of the restrictions on tree felling specified in the Forestry Act 1946. Following the commencement of the Forestry Act 2014 on the 24th May 2017 a Felling and Reforestation policy document was published that provides a consolidated source of information on the legal and regulatory framework relating to tree felling (Forest Service, 2017). Information on the felling licence application process is also described.

Raising awareness of the Forestry Act 2014 and the regulatory framework should be a priority.

4. Prior to the commencment of the Forestry Act 2014 there was no published policy document that established a clear position on the requirements of land owners considering changing land use from forest to all other land uses. A policy document existed in relation to windfarm development only (Forest Service, 2011). However, the recent publication of the Felling and Reforestation policy clearly establishes a policy on deforestation with regard to all other land-use changes, e.g. agriculture. Increased awareness is necessary to ensure the requirements of the various land-use change scenarios are clear for land owners.

5. The Forestry Act 2014 introduced tougher penalties for the illegal felling of trees aimed at maintaining the area of existing forest and helping prevent future deforestation. Most notable are the increased powers concerning replanting orders, which allow the Department of Agriculture, Food and the Marine to issue a replanting order where trees have been felled or otherwise removed without a licence or where the conditions attached to a felling licence have not been observed. In the Forestry Act 1946 a replanting order could not be issued prior to securing summary conviction in the Disctrict Court. However, the Forestry Act 2014 repealed the requirement for a summary conviction to be in place prior to a replanting order being issued. In particular, the use of replanting orders will be required to mitigate against illegal deforestation.

6. This study has confirmed that CORINE data and felling licence information are not suitable for deforestation detection and should not be used for accounting purposes in their current form.

7. A quality assessment of felling licence records revealed erroneous accounts of deforestation in hard-copy applications. One limitation of both general and limited felling licence data is that once licences are granted, they typically remain valid for 1 to 5 years with no system currently in place to track when felling is carried out, if at all. A process whereby notification is given when felling has taken place and a spatial geodatabase is updated following inspection would greatly assist ongoing efforts to develop a semi-automated satellite-based change detection process. The Forestry Act 2014 [Part 3, Section 13(1a)] provides a legal basis for the Minister with responsibility for forestry to request forest owners or managers to furnish information in relation to tree-felling activities.

8. A review of operational national satellite-based automated land-use change detection programmes should be carried out to inform ongoing land-use change accounting developments in Ireland. For example, a semi-automated approach similar to that used in New Zealand (Dymond *et al*., 2012), adapted for SAR-based imagery, may be appropriate for the fragmented Irish landscape.

9. A nationwide study of the potential use of SAR for operational forest cover and annual change detection in Ireland is required. The findings of such a study should incorporate functionality for other land-cover/use types and inform ongoing efforts to develop a national land-cover system in Ireland, including the National Land Cover and Habitat Mapping Programme.

6 Project Outputs

6.1 Peer-reviewed Papers

Devaney, J.L., Barrett, B.W., Barrett, F., Redmond, J.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(8): e0133583.

Devaney, J.L., Redmond, J.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.L., Cott, G.M., Redmond, J.J. and O'Halloran, J., 2016. Deforestation in Ireland 2000–2012; the findings of the DEFORMAP project. *Irish Forestry* 73.

6.2 Conference Presentations

Devaney, J., Barrett, B., Redmond, J. and O'Halloran, J., 2014. Deforestation in Ireland 2000–2012; an assessment of existing and potential estimation techniques, Forest Change 2014, Freising, Germany, April 2014. Oral presentation.

Devaney, J.L., Redmond, J.J. and O'Halloran, J., 2013. Estimation of deforestation in Ireland 2000–2012; a comparison of assessment methods, ENVIRON 2013, National University of Ireland, Galway, February 2013. Oral presentation.

Devaney, J., Barrett, B., Redmond, J., Cawkwell, F. and O'Halloran, J., 2013. Reducing uncertainties associated with deforestation estimation in Ireland using optical and radar sensors, European Space Agency (ESA), Living Planet Symposium, Edinburgh, Scotland, September 2013. Poster presentation.

Devaney, J., Barrett, B., Redmond, J., Cawkwell, F. and O'Halloran, J., 2013. Deforestation estimation in Ireland using optical and radar sensors, 7th Irish Earth Observation Symposium, Teagasc, Ashtown, Dublin, Ireland, 24–25 October 2013. Poster presentation.

6.3 Other

Devaney, J., Redmond, J. and O'Halloran, J., 2014. Is deforestation in Ireland on the increase? *Environews* 28. Magazine article.

Forest Service Inspectors Conference, 2014. The DEFORMAP Project: deforestation estimation and mapping in Ireland 2000–2012. Botanic Gardens of Ireland, Dublin, 10 September 2014. Invited talk.

DEFORMAP: Deforestation Mapping and Estimation in Ireland. School of Biological, Earth and Environmental Science (BEES), UCC, Cork, 9 December 2014. End of project workshop. Project website: https://deformap.wordpress.com/

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Glossary

Afforestation	The direct human-induced conversion of non-forest land to forested land through tree planting, seeding and/or the human-induced promotion of natural seed sources
Clear-felling	Clear-felling (also known as clear-cutting or clearcut logging) is a forestry practice in which most or all trees in an area are uniformly cut down. In Irish forests, most clear-felled areas are subsequently replanted with trees
Cropland	This land-use category includes arable and tillage land, and agroforestry systems where vegetation falls below the thresholds used for the forest land category
Deforestation	The direct human-induced conversion of forested land to non-forested land
Forest	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)*
Geodatabase	A geodatabase is a data structure for geographic information systems (GIS) and is used for managing and editing GIS spatial data
Grassland	Includes rangelands and pasture land that is not considered as cropland. It also includes systems with vegetation that fall below the threshold used in the forest land category and are not expected to exceed, without human intervention, the threshold used in the forest land category
Land cover/land use	Land cover indicates the physical land type such as forest or open water, whereas land use documents how people are using the land
Other land	This land-use category includes all residual land when other land use areas have been determined
Orthophoto	An orthophoto, orthophotograph or orthoimage is an aerial photograph geometrically corrected ("ortho-rectified") such that the scale is uniform: the photo has the same lack of distortion as a map
Photointerpretation	In remote sensing and photogrammetry, photointerpretation is the act of examining photographic images for the purpose of identifying objects and judging their significance
Settlement	This land-use category includes all developed land, including transport infrastructure and human settlements of any size, unless they are already included under other categories
Silvilcultural system	A silvicultural system is the process of tending, harvesting and regenerating a forest. Different objectives in forest management (e.g. conservation in an ancient semi-natural woodland vs production of timber from a conifer plantation) are likely to lead to the adoption of different silvicultural systems
Synthetic aperature radar	Synthetic aperture radar (SAR) is an active microwave remote sensing technology that measures the phase difference between a radar wave emitted from an antennae attached to a satellite or aircraft to generate high-resolution images of a surface
Wetland	Land that is covered or saturated by water for all or part of the year (e.g. peatland) and that does not fall into the forest land, cropland, grassland or settlement categories

Abbreviations

ALOS	Advanced Land Observation Satellite
BP	Before present
CLC	CORINE Land Cover
CORINE	Co-ordination of Information on the Environment
DEFORMAP	Deforestation Estimation and Mapping in Ireland
EC	European Community
ERT	Extremely randomised trees
EU	European Union
FIPS	Forest Inventory and Planning System
GFC	Global Forest Change
GHG	Greenhouse gas
IPCC	Intergovernmental Panel on Climate Change
JRC	Joint Research Centre
LFL	Limited Felling Licence
LiDAR	Light Detection and Ranging
LTO	Lands taken out
LUCAS	Land-Use/Cover Area frame Survey
LULUCF	Land use, land-use change and forestry
LUT	Land-use transition
NFI	National Forest Inventory
NIR	National Inventory Report
OSi	Ordnance Survey Ireland
PALSAR	Phased array type L-band synthetic aperture radar
RF	Random forests
SAR	Synthetic aperture radar
UNFCCC	United Nations Framework Convention on Climate Change

AN GHNÍOMHAIREACHT UM CHAOMHNÚ COMHSHAOIL
Tá an Ghníomhaireacht um Chaomhnú Comhshaoil (GCC) freagrach as an gcomhshaol a chaomhnú agus a fheabhsú mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ó éifeachtaí díobhálacha na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialú: *Déanaimid córais éifeachtacha rialaithe agus comhlíonta comhshaoil a chur i bhfeidhm chun torthaí maithe comhshaoil a sholáthar agus chun díriú orthu siúd nach gcloíonn leis na córais sin.*

Eolas: *Soláthraímid sonraí, faisnéis agus measúnú comhshaoil atá ar ardchaighdeán, spriocdhírithe agus tráthúil chun bonn eolais a chur faoin gcinnteoireacht ar gach leibhéal.*

Tacaíocht: *Bímid ag saothrú i gcomhar le grúpaí eile chun tacú le comhshaol atá glan, táirgiúil agus cosanta go maith, agus le hiompar a chuirfidh le comhshaol inbhuanaithe.*

Ár bhFreagrachtaí

Ceadúnú
Déanaimid na gníomhaíochtaí seo a leanas a rialú ionas nach ndéanann siad dochar do shláinte an phobail ná don chomhshaol:
- saoráidí dramhaíola *(m.sh. láithreáin líonta talún, loisceoirí, stáisiúin aistrithe dramhaíola)*;
- gníomhaíochtaí tionsclaíocha ar scála mór *(m.sh. déantúsaíocht cógaisíochta, déantúsaíocht stroighne, stáisiúin chumhachta)*;
- an diantalmhaíocht *(m.sh. muca, éanlaith)*;
- úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe *(OGM)*;
- foinsí radaíochta ianúcháin *(m.sh. trealamh x-gha agus radaiteiripe, foinsí tionsclaíocha)*;
- áiseanna móra stórála peitril;
- scardadh dramhuisce;
- gníomhaíochtaí dumpála ar farraige.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil
- Clár náisiúnta iniúchtaí agus cigireachtaí a dhéanamh gach bliain ar shaoráidí a bhfuil ceadúnas ón nGníomhaireacht acu.
- Maoirseacht a dhéanamh ar fhreagrachtaí cosanta comhshaoil na n-údarás áitiúil.
- Caighdeán an uisce óil, arna sholáthar ag soláthraithe uisce phoiblí, a mhaoirsiú.
- Obair le húdaráis áitiúla agus le gníomhaireachtaí eile chun dul i ngleic le coireanna comhshaoil trí chomhordú a dhéanamh ar líonra forfheidhmiúcháin náisiúnta, trí dhíriú ar chiontóirí, agus trí mhaoirsiú a dhéanamh ar leasúchán.
- Cur i bhfeidhm rialachán ar nós na Rialachán um Dhramhthrealamh Leictreach agus Leictreonach (DTLL), um Shrian ar Shubstaintí Guaiseacha agus na Rialachán um rialú ar shubstaintí a ídíonn an ciseal ózóin.
- An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Uisce
- Monatóireacht agus tuairisciú a dhéanamh ar cháilíocht aibhneacha, lochanna, uiscí idirchriosacha agus cósta na hÉireann, agus screamhuiscí; leibhéil uisce agus sruthanna aibhneacha a thomhas.
- Comhordú náisiúnta agus maoirsiú a dhéanamh ar an gCreat-Treoir Uisce.
- Monatóireacht agus tuairisciú a dhéanamh ar Cháilíocht an Uisce Snámha.

Monatóireacht, Anailís agus Tuairisciú ar an gComhshaol
- Monatóireacht a dhéanamh ar cháilíocht an aeir agus Treoir an AE maidir le hAer Glan don Eoraip (CAFÉ) a chur chun feidhme.
- Tuairisciú neamhspleách le cabhrú le cinnteoireacht an rialtais náisiúnta agus na n-údarás áitiúil *(m.sh. tuairisciú tréimhsiúil ar staid Chomhshaol na hÉireann agus Tuarascálacha ar Tháscairí)*.

Rialú Astaíochtaí na nGás Ceaptha Teasa in Éirinn
- Fardail agus réamh-mheastacháin na hÉireann maidir le gáis cheaptha teasa a ullmhú.
- An Treoir maidir le Trádáil Astaíochtaí a chur chun feidhme i gcomhair breis agus 100 de na táirgeoirí dé-ocsaíde carbóin is mó in Éirinn.

Taighde agus Forbairt Comhshaoil
- Taighde comhshaoil a chistiú chun brúnna a shainaithint, bonn eolais a chur faoi bheartais, agus réitigh a sholáthar i réimsí na haeráide, an uisce agus na hinbhuanaitheachta.

Measúnacht Straitéiseach Timpeallachta
- Measúnacht a dhéanamh ar thionchar pleananna agus clár beartaithe ar an gcomhshaol in Éirinn *(m.sh. mórphleananna forbartha)*.

Cosaint Raideolaíoch
- Monatóireacht a dhéanamh ar leibhéil radaíochta, measúnacht a dhéanamh ar nochtadh mhuintir na hÉireann don radaíocht ianúcháin.
- Cabhrú le pleananna náisiúnta a fhorbairt le haghaidh éigeandálaí ag eascairt as taismí núicléacha.
- Monatóireacht a dhéanamh ar fhorbairtí thar lear a bhaineann le saoráidí núicléacha agus leis an tsábháilteacht raideolaíochta.
- Sainseirbhísí cosanta ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Faisnéis Inrochtana agus Oideachas
- Comhairle agus treoir a chur ar fáil d'earnáil na tionsclaíochta agus don phobal maidir le hábhair a bhaineann le caomhnú an chomhshaoil agus leis an gcosaint raideolaíoch.
- Faisnéis thráthúil ar an gcomhshaol ar a bhfuil fáil éasca a chur ar fáil chun rannpháirtíocht an phobail a spreagadh sa chinnteoireacht i ndáil leis an gcomhshaol *(m.sh. Timpeall an Tí, léarscáileanna radóin)*.
- Comhairle a chur ar fáil don Rialtas maidir le hábhair a bhaineann leis an tsábháilteacht raideolaíoch agus le cúrsaí práinnfhreagartha.
- Plean Náisiúnta Bainistíochta Dramhaíola Guaisí a fhorbairt chun dramhaíl ghuaiseach a chosc agus a bhainistiú.

Múscailt Feasachta agus Athrú Iompraíochta
- Feasacht chomhshaoil níos fearr a ghiniúint agus dul i bhfeidhm ar athrú iompraíochta dearfach trí thacú le gnóthais, le pobail agus le teaghlaigh a bheith níos éifeachtúla ar acmhainní.
- Tástáil le haghaidh radóin a chur chun cinn i dtithe agus in ionaid oibre, agus gníomhartha leasúcháin a spreagadh nuair is gá.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil
Tá an ghníomhaíocht á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóirí. Déantar an obair ar fud cúig cinn d'Oifigí:
- An Oifig um Inmharthanacht Comhshaoil
- An Oifig Forfheidhmithe i leith cúrsaí Comhshaoil
- An Oifig um Fianaise is Measúnú
- Oifig um Chosaint Radaíochta agus Monatóireachta Comhshaoil
- An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tá Coiste Comhairleach ag an nGníomhaireacht le cabhrú léi. Tá dáréag comhaltaí air agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.

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21st Century Deforestation in Ireland

Authors: John Devaney, John Redmond, Brian Barrett, Grace Cott and John O'Halloran

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Identifying pressures • Informing policy • Developing solutions

Identifying pressures

As a result of extensive afforestation, Ireland's forest carbon makes a substantial contribution to national greenhouse gas (GHG) reduction targets. Deforestation (i.e. the permanent change of forest to non-forest land-use) could have a significant impact on GHG emissions in Ireland's National Inventory Report to the United Nations Framework Convention on Climate Change (UNFCCC). Large uncertainties are associated with current estimates of national deforestation. Consequently, a spatially explicit quantification of the extent and character of contemporary deforestation in Ireland is required to assess the validity of existing and potential future deforestation estimation methodologies.

Informing policy

This study provides the first national map of contemporary deforestation events in Ireland. The study reports that National Forest Inventory reporting is currently the most accurate source of deforestation estimation in Ireland. However, to improve accuracy, a national-scale photointerpretation of deforestation areas could be repeated on a cyclical basis using updated national imagery datasets. A preliminary study of the potential application of Synthetic Aperture Radar satellite data (SAR) to forest monitoring in Ireland indicated that radar remote sensing, used in combination with photointerpretation and ground survey, offers a valuable tool for future forest change accounting in Ireland. A high rate of deforestation of privately owned broadleaf forests is also reported. These findings will inform future policy decisions on GHG accounting and the long term protection of Irish forests.

Developing solutions

This research provides evidence-based recommendations for the development of forest related land-use change accounting methodologies in Ireland. The work outlined here will reduce uncertainties in GHG emissions reporting and contribute to the development of national land-use/land cover change mapping.

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