Applied Geography 63 (2015) 346–356

Contents lists available at ScienceDirect

Applied Geography

journal homepage: www.elsevier.com/locate/apgeog

Contemporary forest loss in Ireland; quantifying rare deforestation events in a fragmented forest landscape

John L. Devaney [a, *], John J. Redmond [b], John O'Halloran [a]

[a] School of Biological Earth and Environmental Sciences (BEES), University College Cork (UCC), Cork, Ireland
[b] Forest Service, Dept. of Agriculture, Food and the Marine, Johnstown Castle, Wexford, Ireland

ARTICLE INFO

Article history:
Received 22 April 2015
Received in revised form
14 July 2015
Accepted 14 July 2015
Available online 31 July 2015

Keywords:
Deforestation
Ireland
UNFCCC
National Forest Inventory
Land-use change
CORINE

ABSTRACT

Accurate quantification of forest loss is required to meet international reporting requirements, even in countries where deforestation rates are low. In Ireland, recent evidence has suggested the rate of gross annual deforestation is increasing. However, no spatially explicit data on the extent and character of contemporary deforestation exists. Here, we quantify deforestation in a region where forest loss is rare. Deforestation estimates derived from wall-to-wall photointerpretation, official records (e.g. felling licences), the CORINE land-use/land cover changes dataset and a combined approach (hereafter termed "the Deforestation Map") are compared in two regions in Ireland for the period 2000 to 2012. Deforestation area based on the Deforestation Map (1497 ha) was greater than estimates derived from using photo-interpretation (730 ha), official records (908 ha) and CORINE (139 ha) alone. Independent accuracy assessment highlighted high errors of omission for photo-interpretation (68.9%), official records (66.7%) and CORINE (91.84%) estimates compared to the Deforestation Map (20%). No general increase in the deforestation rate during the study period was recorded, despite regional variations. Post deforestation land-use transitions were principally to wetland, grassland and settlement although the magnitude and proportion of change varied regionally. Gross annual deforestation was higher in older broadleaf forests than in conifer plantation forests, a surprising finding considering the small area and conservation status of many broadleaf forests in Ireland. For countries with small forest area and/or low rates of deforestation, the use of methodologies employed herein can provide a valuable record of forest loss and be used to validate sample-based or remotely sensed deforestation estimates.

1. Introduction

The conversion of forest land to non-forest land contributes 6–17% of global anthropogenic CO_2 emissions to the atmosphere (Van der Werf et al., 2009) and is a principal driver of human-induced climate change (Ashton, Tyrrell, Spalding, & Gentry, 2012; Bonan, 2008). Due to high rates of deforestation, efforts have focused on the large-scale assessment of forest cover loss in tropical regions (Achard et al., 2007; Asner et al., 2010; Hansen et al., 2008). Quantification of changes in forest land-use in countries with low forest cover and/or where deforestation is rare is nonetheless required to meet international reporting obligations (Leckie, Gillis, & Wulder, 2002; Levy & Milne, 2004; UNFCCC, 1997). Tracking patterns of forest land-use on local and regional scales can also inform biodiversity conservation and ecosystem services management (Pettorelli et al., 2005; Turner et al., 2003; Zhao et al., 2004).

Changes in the extent of forest cover are often quantified using a range of automated and semi-automated satellite-based remote sensing approaches (Hansen et al., 2008; Portillo-Quintero et al., 2012; Potapov et al., 2012). 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 (Lister, Lister, & Alexander, 2014). While such issues can be overcome using products such as higher resolution imagery, LiDAR and object-based image analysis, these tools can require advanced expertise and resource investment not always available to regional or national reporting organisations (Lister et al., 2014). 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 where the principal silvicultural method is clear-cutting followed by replanting. Clear-cutting is generally associated with a marked

* Corresponding author. Current address: Smithsonian Environmental Research Centre, 647 Contees Wharf, Edgewater, MD, 21037, USA.
E-mail address: devaneyj@si.edu (J.L. Devaney).

http://dx.doi.org/10.1016/j.apgeog.2015.07.008
0143-6228/

change in backscatter signal (Bucha & Stibig, 2008), but differentiating clear-cutting forest management operations from permanent land-use change may require ground survey or manual photo-interpretation of imagery.

Manual interpretation of high resolution aerial photography and satellite imagery has been shown to offer an accurate and cost effective alternative to automated approaches to identifying regional land-use changes (Lister et al., 2014; Nowak & Greenfield, 2012). Detecting land-use change using manual photo-interpretation is generally carried out via interpreting a statistical sample of imagery of defined area (known as a photo-plot) (e.g. Ecke, Magnusson, & Hörnfeldt, 2013; Magnussen & Russo, 2012) or a stratified sample of points or pixels (Lister et al., 2014; Nowak & Greenfield, 2010). When land-use change events are rare, sub-samples of imagery may not be sufficient to provide accurate quantification of change areas (Dymond, Shepherd, Arnold, & Trotter, 2008). 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 photo-interpretation for monitoring forest land-use change may be appropriate for regions or small countries with rare, fine-scale deforestation events, and/or operating a predominantly clear-cut – replant forest management system.

Although the natural vegetation cover of much of Ireland is forest (Cross, 2006), by 1900 forest cover was <1% following millennia of deforestation (Mitchell, 2000). Since then both state and private afforestation has increased forest cover to 10.5% (Forest Service, 2013). In recent times, newly afforested areas have generally been small, privately owned land parcels, driven by grant payments from the government and the European Union (O'Donnell, Cummins, & Byrne, 2013). This has resulted in a highly fragmented forest landscape in Ireland, with privately owned forests being on average <11 ha in size (COFORD, 2009). The fragmented nature of forest cover, and a national forest size definition of just >0.1 ha, dictates that deforestation events are generally small, fragmented and difficult to quantify.

Recent evidence from Ireland's National Forest Inventory (NFI) suggests that the gross national annual deforestation rate is increasing (Forest Service, 2007; Forest Service, 2013). As in many other countries (Tomppo, Gschwantner, Lawrence, & McRoberts, 2010), NFI information is used for reporting deforestation areas under the Land-Use, Land-Use Change and Forestry (LULUCF) sector of Ireland's National Inventory Report (NIR) on greenhouse gas emissions to the United Nations Framework Convention on Climate Change (UNFCCC) (Duffy et al., 2014). However, deforestation estimates based on this sample based methodology are associated with a high level of uncertainty (up to 50%). In addition, due to its sample based design, NFI derived deforestation estimates can only be applied on a national scale and are not useful for monitoring change on regional or local scales. Currently, on a local, regional or national scale, no spatially explicit data on the extent and character of contemporary deforestation in Ireland exists.

Here, we quantify the extent and causes of deforestation in regions where forest loss is rare. The principal objective of the study was to assess the nature of deforestation in two study regions in Ireland for the period 2000 to 2012. Deforestation area estimates derived from using wall-to-wall photointerpretation, official records, and a semi-automated approach are compared. For the purposes of this analysis, the forest definition used for international forest reporting in Ireland (land with a minimum area of 0.1 ha, trees >5 m in height and canopy cover ≥20%) has been adopted.

2. Materials and methods

2.1. Study areas

The study areas encompassed the northwest region (counties Donegal, Mayo and Sligo) and the midlands region (counties Offaly, Laois and Tipperary) of Ireland (Fig. 1). The northwest (12,285 km^2)

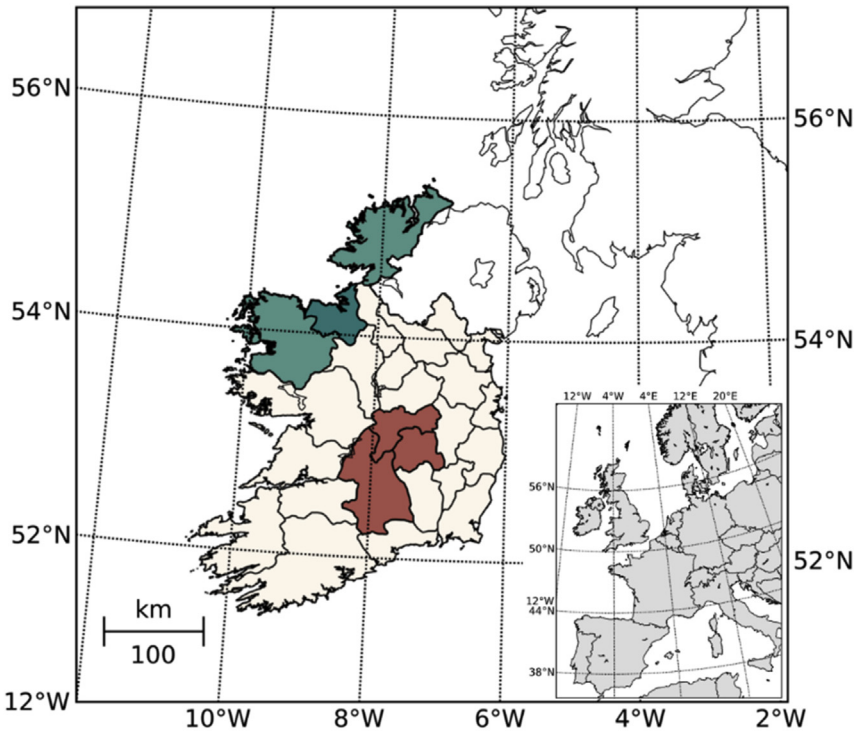

Fig. 1. Location of the northwest (shaded green) and midlands (shaded red) study regions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and midlands (8026 km^2) study areas constitute 17.5% and 11.4% of the total land area of the Republic of Ireland respectively. The northwest is characterised by numerous upland areas such as the Derryveagh, Blue Stack and Nephin Beg mountains. Soil type is dominated by blanket and cutover peats and shallow rocky peaty mineral soils (Gardiner & Ryan, 1969). Principal land-use/land-cover in the region include peat bog and heath. The midlands study area is of predominantly lowland topography apart from the Slieve Bloom and Silvermines mountains and upland areas of south Tipperary. In contrast to the northwest, well drained mineral soils are most common in the midlands study area (Gardiner & Ryan, 1969). Consequently, principal land-use/land-cover is more agricultural, with pasture grassland being the most frequent.

There is considerable variation in the extent and nature of forest cover between the two study regions. The northwest has 10.7% forest cover whereas forest cover in the midlands is 12.7% (Forest Service, 2013). Forest cover in the northwest is dominated by large areas of state-owned non-native conifer plantations in upland regions. Sitka spruce (*Picea sitchensis*) and lodgepole pine (*Pinus contorta*) are the main forest tree species in the northwest accounting for 55.9% and 19.3% of the stocked forest area respectively. Native forest tree species account for only 17.4% in the region. Although non-native conifer species Sitka spruce and Norway spruce (*Picea abies*) are the most common forest tree species (42.2% and 8.7% of the stocked forest area respectively), native species (principally ash *Fraxinus excelsior*, birch *Betula pubescens* and oak *Quercus* spp.) are more common (28.5% of the forest area) in the midlands (Forest Service, 2013). In total, 31% of the national forest area is included in this study (18% in the northwest and 13% in the midlands).

2.2. Photo-interpretation

To identify deforestation areas, complete wall-to-wall manual photo-interpretation (PI) of high-resolution imagery was carried out for the study areas. Three series of digital orthorectified aerial photography were used: Ordnance Survey Ireland 2000, 2005 and 2010 orthophotos at a scale of 1:40000 and pixel size of 1 m. High resolution (<1 m) optical satellite imagery, captured between November 2011 and May 2012, was also obtained through the Bing Maps base imagery layer in ArcGIS 10. In ArcGIS 10 the fishnet tool was used to create a grid of 2 × 2 km photo-plots in the study areas (Fig. 2). In total, 5112 photo-plots were interpreted at a scale of 1:8500. A single interpreter was trained and conducted all PI. A time-series visual assessment of co-registered imagery for each photo-plot was carried out to identify temporal trends in deforestation events during three time intervals: 2000–2005, 2005–2010 and 2010–2012. The UNFCCC definition of deforestation was used i.e. the direct human-induced conversion of forested land to non-forested land (Penman et al., 2003). Two existing forest vector

Fig. 2. Example of 2 × 2 km photo-plot 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). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

datasets were used to aid interpretation: (1) the most recent national forest cover map (Forestry2012) (2) the Irish National Survey of Native Woodlands (Perrin et al., 2008) spatial dataset of native woodlands in Ireland. The spatial extent of each identified deforestation event was digitised and a suite of attributes were recorded. Post deforestation land-use transition was interpreted based on imagery and/or ground survey. Recording of LUTs were based on UNFCCC land-use reporting categories, namely forest, settlement, grassland, cropland, wetland and other land (UNFCCC, 1992). For deforested areas, three categories of forest type (conifer, mixed and broadleaf), age class (<20 years, 20–40 years, > 40 years) and pre-deforestation land ownership (state established, private grant-aided and private non-grant aided) were recorded based on information in forest vector datasets. The term "state established" was applied to forests that were afforested by the state but may have been sold into private ownership prior to deforestation activity. In limited cases (<20%) where information was not available in existing inventory datasets, pre-deforestation forest type and age categories where determined based on imagery interpretation. A PI attribute classification accuracy procedure was carried out whereby a sub-sample of deforestation areas were re-interpreted by a second expert photo-interpreter (Tables S1–S3).

2.3. Official deforestation records

Existing sources of deforestation information for the study areas were compared with estimates derived solely from PI. In Ireland, the felling of trees is regulated by the Forest Service. The 1946 Forestry Act (Government of Ireland, 1946) provides the legal basis for this regulation. Land owners require permission from the Irish Forest Service for deforestation activities in the form of limited felling licences (LFLs). 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. Records of LFLs contain information on the area and location of deforested land and are maintained by the Forest Service. The spatial extent of LFL deforested areas in our study regions were digitised in ArcGIS 10 based on hard-copy maps provided in licence applications. From 2002 to 2008, Coillte Teoranta (state forestry company) and other agencies undertook active raised and blanket bog habitat restoration projects under the European Union LIFE funding mechanism. Spatial information on restoration activities involving the conversion of forest land-use to wetland land-use was obtained from Coillte Teoranta and digitised. Under reporting definitions, forest areas remaining unstocked for >5 years are deemed to be deforested (Duffy et al., 2014). Supplementary data on areas potentially remaining unstocked for >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 2012 were extracted. Due to difficulties differentiating between areas identified as remaining unstocked for >5 years and recently replanted forest using imagery alone, all such areas were ground surveyed to verify current land-use. As with the PI dataset, post deforestation LUTs were interpreted using imagery and forest type was determined using ancillary forest datasets. For the purposes of this study, combined LFL, bog restoration and unstocked areas information are termed "official records" of deforestation. These sources have previously been used in combination with NFI data for national deforestation reporting in Ireland (Duffy et al., 2012).

2.4. CORINE land cover changes 2000–2012

The Co-ordination of Information on the Environment (CORINE) programme was established in 1985 with the aim of providing land-cover/land-use information for Europe (Bossard, Feranec, & Otahel, 2000). Using a semi-automated approach, pan-European datasets of classified land-cover types are available for 1990 (CORINE land cover (CLC) 1990), 2000 (CLC 2000) and 2006 (CLC 2006) and 2012 (CLC 2012). CORINE data has previously been used to examine changing land-use patterns in Europe (Eaton, McGoff, Byrne, Leahy, & Kiely, 2008; Falcucci, Maiorano, & Boitani, 2007; Feranec, Jaffrain, Soukup, & Hazeu, 2010, 2007). For Ireland, Landsat 5 TM, Landsat 7 ETM, SPOT 4/5 and IRS-P6-LISSIII satellite imagery was used, in combination with ancillary dataset to create a 2000–2012 national land-use/land-cover change dataset (Lydon & Smith, 2014). CORINE uses a hierarchical classification system containing 44 land cover categories (Feranec et al., 2010). For our study regions, areas changing from forest land-use/land cover categories (311 broadleaved 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 deforestation estimate comparison with PI and official records.

2.5. Combined approach; The Deforestation Map

To assess whether using PI, official records, CLC 2000–2012 estimates or a combined approach produced the most accurate map of forest loss, deforestation areas based on official records and CLC 2000–2012 were combined with the PI dataset to create a geodatabase of deforestation events in the study regions during 2000–2012, hereafter termed the "Deforestation Map". All official records of deforestation were verified using imagery. Where the spatial extent of deforestation events recorded in official records and CLC 2000–2012 differed from their spatial extent based on imagery interpretation, deforestation polygons were modified to represent their extent as indicated by imagery. The process by which the combined Deforestation Map was created is outlined in Fig. 3. Imagery reinterpretation, ground survey and accuracy assessment procedures were carried out to maximise the usability of the final Deforestation Map. In cases where the occurrence of deforestation or LUT was uncertain based on imagery interpretation, polygons were reviewed by one or more expert photo-interpreters. Where uncertainty remained following reinterpretation, ground surveys were carried out. In total, 119 sites were ground surveyed to verify deforestation activity (accounting for 48% of the final deforestation area).

2.6. Quality assurance and accuracy assessment

An independent accuracy assessment was carried out using imagery point sampling and ground survey plots. A previous version of the semi-automated 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 with supplementary data from panchromatic orthophotos and OSi 25" map series. Within Forest2000, 3000 stratified randomly located points were generated in ArcGIS 10. 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 (>80% of the study areas), which was used as 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 9 pixels) were visually interpreted by five photo interpreters. Only areas where a clear non-forest land-use was evident in 2012 were recorded as deforestation (i.e. clear-felled areas in post 2011 GoogleEarth imagery areas were not deemed as deforestation). In addition, independent ground survey points were added to the accuracy assessment

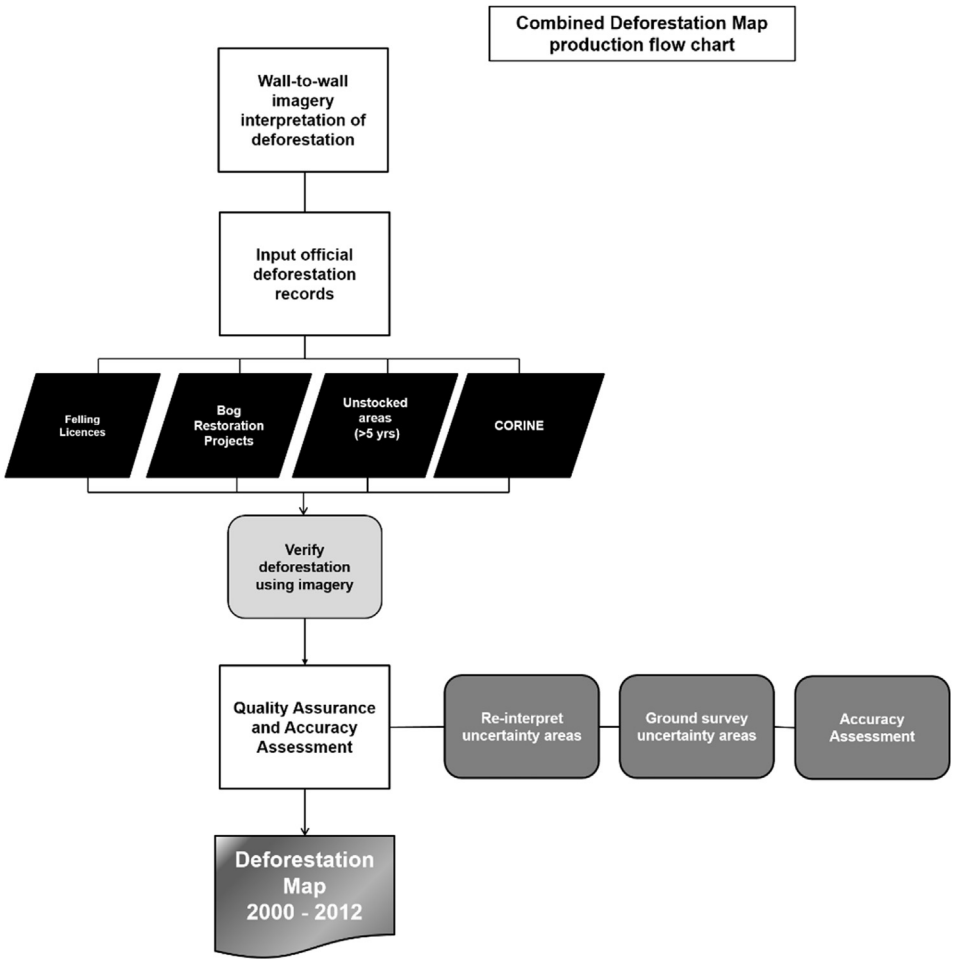

Fig. 3. Flowchart of production of the Deforestation Map used for determining area and nature of deforestation events in the northwest and midlands study areas for the period 2000–2012.

dataset. LUCAS (Land Use/Cover Area frame Survey) is a ground-based survey, with direct observations of land use recorded by field surveyors at 270,000 permanent sampling units throughout the European Union in 2012. All LUCAS plots occurring within Forest2000 were added to the accuracy assessment dataset (n = 109). In our study area, NFI forest plots were independently established in 2004 based on imagery interpretation and ancillary data (n = 541). These plots were ground surveyed 2004–2006 and again in 2011–2012 to determine current land-use. LUCAS, NFI ground survey plots and Google Earth interpretation points were combined into one reference dataset (total n = 3650). Producer's accuracy (the proportion of area in a category in reference data that is also mapped as that category), user's accuracy (the proportion of the area mapped as a particular category that is actually that category in reference data) and overall accuracy (the proportion of the area mapped correctly) of forest land/deforested land maps was calculated following standards methods (Olofsson, Foody, Herold, & Stehman, 2014).

3. Results

3.1. Gross deforestation area and rate from different methodologies

Considerable spatial and temporal variation in deforestation rate between study areas was evident based on the Deforestation Map (Figs. 4 and 5). The total area of deforested land in northwest study area was 1091.73 ha, corresponding to a gross annual deforestation rate of 0.064% (Table 1). In comparison, the gross annual deforestation rate in the midlands study area was 0.032% (deforestation area; 405.68 ha). Although the density of deforestation events in both areas was comparable (Table 1), the mean area of deforestation event in the northwest was almost double that of the equivalent value for the midlands. The Deforestation Map approach was compared with maps derived solely from PI, official records and a semi-automated approach (Figs. 4 and 5; Table 1). For both study areas, PI, official records and CORINE estimates for deforestation area were considerably lower than Deforestation Map estimate (Table 1). In the northwest, total deforestation area based on official records was 762.37 ha, with 513.2 ha of this attributable to bog habitat restoration activities. In the midlands, total deforestation area based on official records was 145.25 ha, suggesting a large number of unreported forest loss areas. Based on official records and CORINE, average size of deforestation event in the northwest was 6.03 ha and 9.9 ha respectively, a six-fold and nine-fold increase on the corresponding value for PI derived estimates, indicating potential underrepresentation of small-scale deforestation events.

Overall accuracies of forest land/deforested land maps were high for PI, official records and the Deforestation Map (Table 2). 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

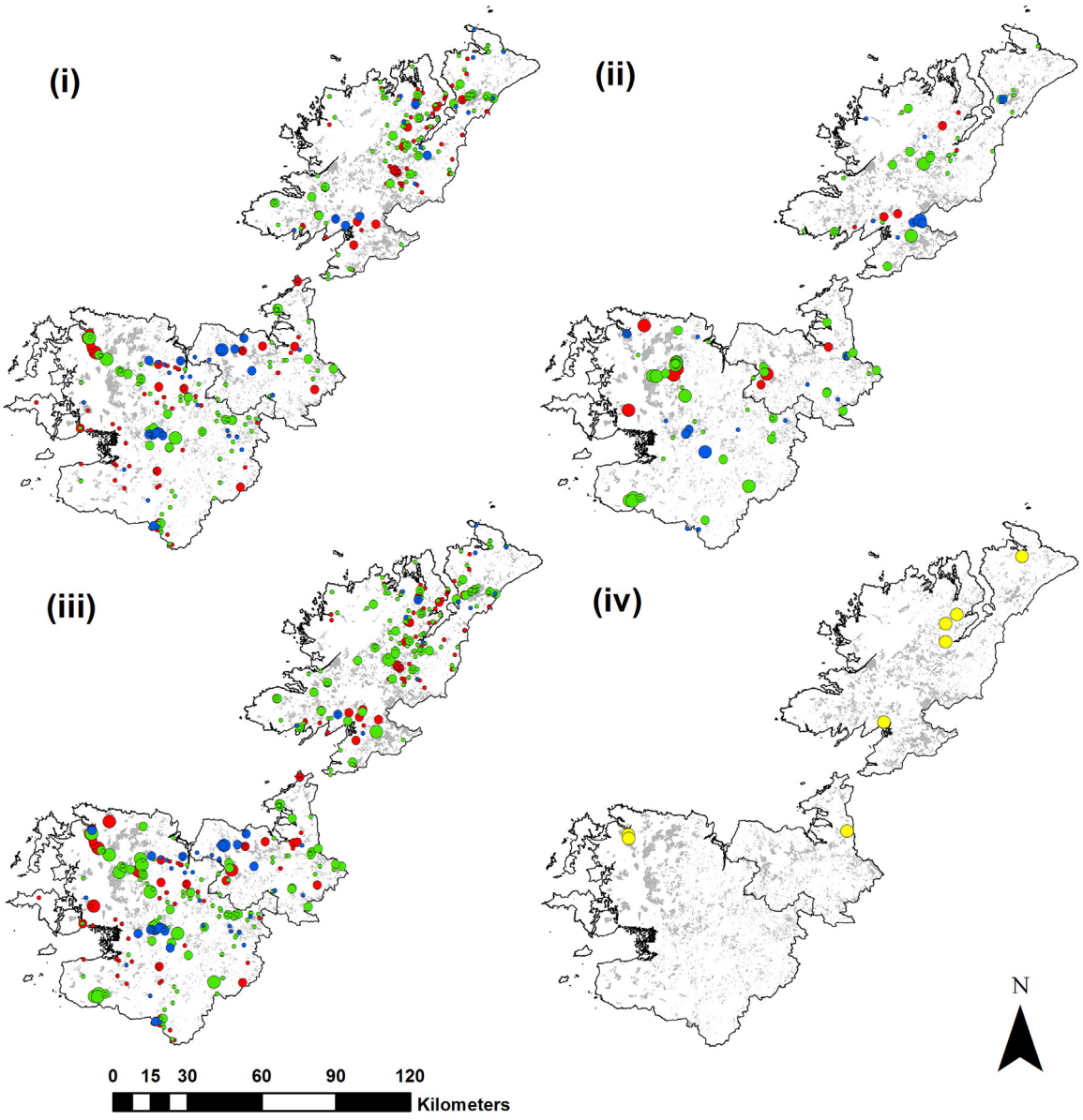

Fig. 4. Spatial and temporal distribution of deforestation events in the northwest 2000–2012 based on (i) photo-interpretation (ii) official records (iii) the Deforestation Map and (iv) CORINE Changes 2000 - 2012. Red points represent deforestation events 2000–2005, green points represent deforestation events 2005–2010 and blue 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 and 10 ha in size and largest points are representative of deforestation events >10 ha in size. The extent of forest cover in the region is shown in grey. Deforestation events 2000–2012 as indicated by CORINE Changes 2000 – 2012 is indicated by yellow points. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

>90% for PI, official records and the Deforestation Map, indicating that, in general, loss of forest land-use was correctly identified as deforested land based on reference data. For CORINE derived data, user's accuracy was only 66.7%, indicating that many areas classified as deforested remained in forest land-use based on reference data. For CORINE, official records and PI derived maps, producer's accuracy was only 8.16%, 31.1% and 33.3% respectively, highlighting large omissions of deforested land. For the Deforestation Map, the producer's accuracy was 80% indicating a more accurate quantification of deforestation areas, despite some omissions.

3.2. Post deforestation land-use transitions

Given the higher accuracy of the combined approach, further analysis focused on the findings of the Deforestation Map. For each deforestation event, post deforestation LUT was determined based on imagery interpretation and/or ground survey. In general, LUTs were to wetland, grassland and settlement although marked temporal and regional variations were evident (Fig. 6). For example, forest-wetland transitions represented the largest proportional area in the northwest, accounting for 64% of total deforestation. Forty-seven percent (513.7 ha) of the deforestation area in the northwest was attributable to blanket bog habitat restoration activities. In the northwest, annual forest–wetland deforestation increased from 56.8 ha a^{-1} during the 2000–2005 period to 74.4 ha a^{-1} in 2005–2010 but decreased sharply during the 2010–2012 to 11.9 ha a^{-1}. The area of forest-grassland conversions in the northwest increased in consecutive periods, from 8.9 ha a^{-1} during 2000–2005 to 28.6 ha a^{-1} in 2010–2012. In contrast, forest-wetland areas accounted for only 3.7% of total

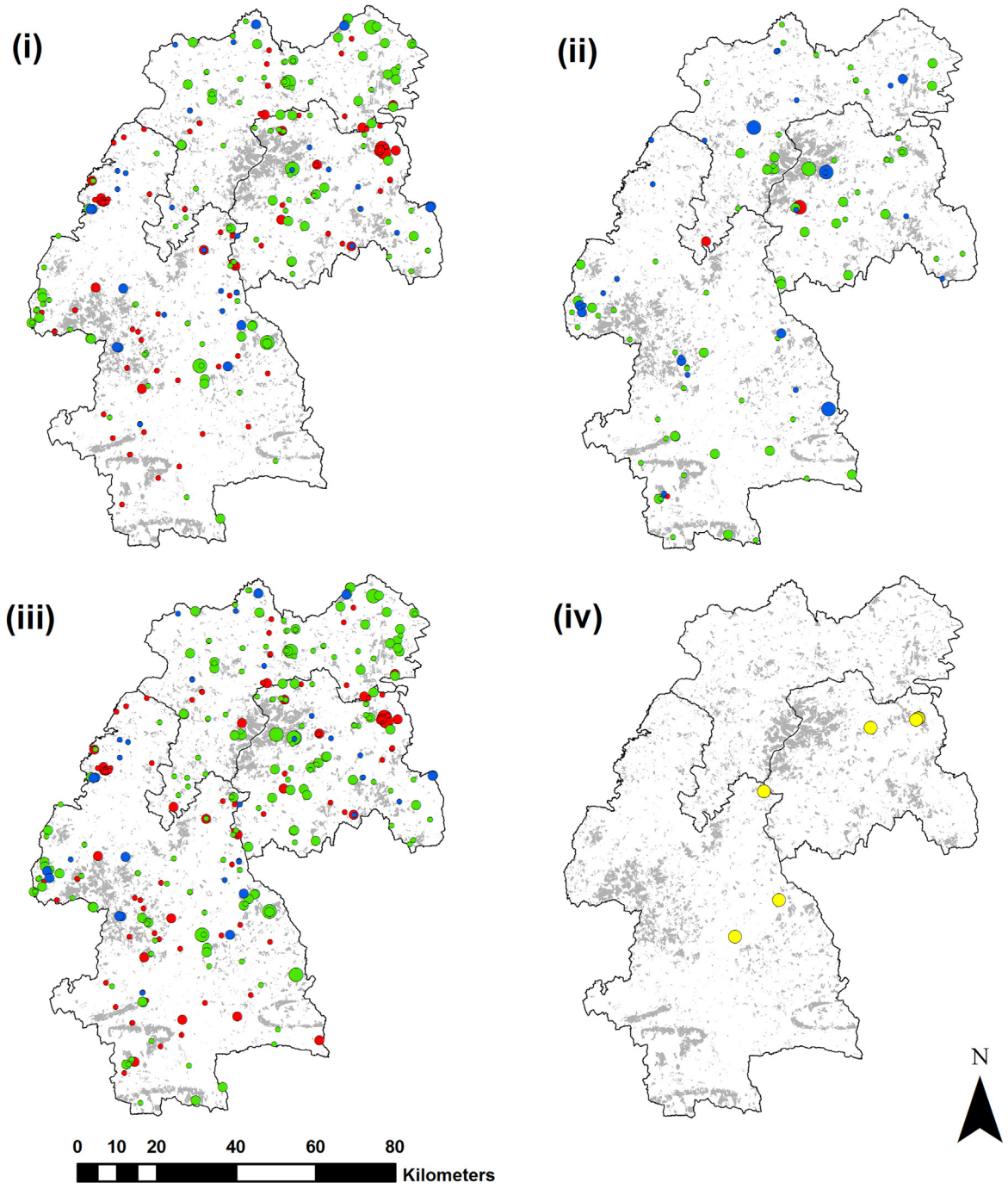

Fig. 5. Spatial and temporal distribution of deforestation events in the midlands 2000–2012 based on (i) photo-interpretation (ii) official records (iii) the Deforestation Map and (iv) CORINE Changes 2000 – 2012. Red points represent deforestation events 2000–2005, green points represent deforestation events 2005–2010 and blue 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 and 10 ha in size and largest points are representative of deforestation events >10 ha in size. The extent of forest cover in the region is shown in grey. Deforestation events 2000–2012 as indicated by CORINE Changes 2000 – 2012 is indicated by yellow points. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

deforestation in the midlands. Principal post deforestation LUTs were grassland and settlement. The rate of conversion of forest to grassland and settlement in the midlands increased approximately two-fold between the 2000–2005 period and the 2005–2010 period, but decreased during the 2010–2012. In both regions, conversions from forest to other land was low, constituting only 3% and 1.2% of the total deforestation in the northwest and midlands respectively.

3.3. Forest type, age and ownership deforestation rates

We assessed the rate of deforestation in forest type, age and ownership categories. The area (±95% confidence intervals) of conifer, mixed and broadleaf forest in each forest age category based on NFI statistics (Table S4) was used to calculate the max-min range of deforestation rates in each category for both study regions (Fig. 7). Trends for deforestation in different age categories followed

Table 1
Deforestation area (ha), annual rate (% a^{-1}), number and density of deforestation events and mean size (ha) of deforestation event in the northwest and midlands study regions for the period 2000–2012 based on photo-interpretation, official records, CORINE and the Deforestation Map.

Deforestation	Northwest				Midlands			
	Photo-interpretation	Official records	CORINE	Deforestation map	Photo-interpretation	Official records	CORINE	Deforestation map
Area (ha)	427.25	762.37	79.20	1091.73	302.79	145.25	60.20	405.68
Rate (%)	0.029	0.043	0.005	0.064	0.025	0.015	0.005	0.032
No. events	425	121	8	513	274	104	8	343
Density (n/km2)	0.035	0.010	0.0007	0.042	0.034	0.013	0.001	0.044
Mean area of event (ha)	1.01	6.03	9.90	2.13	1.11	1.40	7.53	1.18

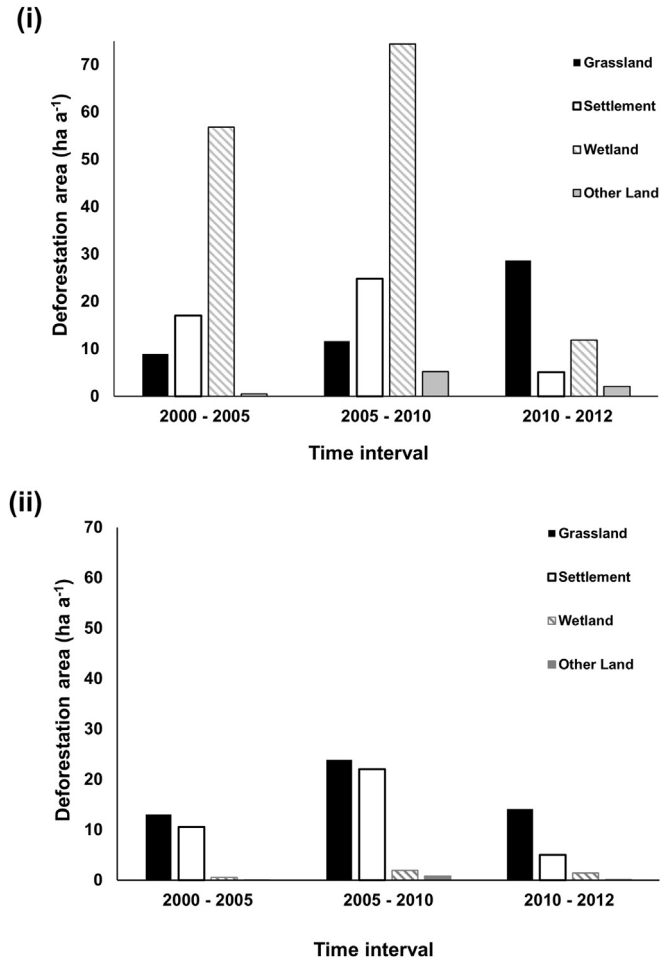

Fig. 6. Annual area (ha a^{-1}) of post-deforestation land-use transitions in the northwest (i) and midlands (ii) during 2000–2005, 2005–2010 and 2010–2012 based on Deforestation Map estimates.

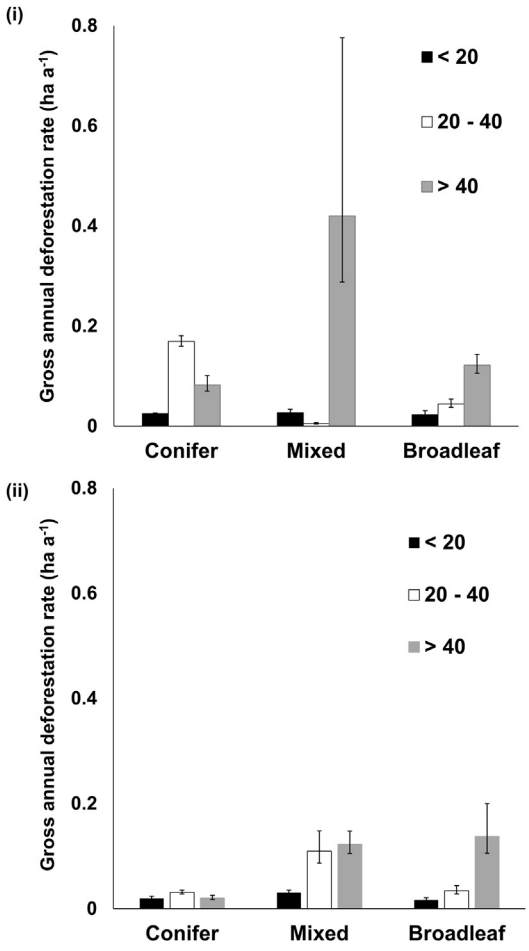

Fig. 7. Gross annual deforestation rate (% a^{-1}) in three forest types and three age classes in the northwest (i) and midlands (ii) study regions. Errors bars indicate the max-min range of values based on 95% confidence intervals of conifer, mixed and broadleaf forest area in each forest age category based on NFI statistics (Table S4).

similar patterns in both regions. For conifer dominated forests, gross annual deforestation rate was highest in the 20–40 years category in the northwest and midlands; 0.18% and 0.031% respectively. In contrast, for mixed and broadleaf dominated forests, gross annual deforestation rate increased with forest age (Fig. 7). The large range in estimated deforestation rate for mixed >40 year old forest in the northwest is a consequence of the low proportional total area and associated large confidence intervals for that forest type in the northwest (Table S4). In the midlands, the gross annual deforestation rate was greater in mixed and broadleaf forests compared with conifer forests (Fig. 7). The rate of deforestation of state established forests was approximately five times greater than in privately owned forest in the northwest region (Fig. 8). Although deforestation was highest in the private grant-aided ownership class, rates of forest loss were broadly similar across all ownership classes in the midlands (Fig. 8).

4. Discussion

4.1. Deforestation estimation in Ireland

Based on this study, the combined deforestation area of both study regions was 1497 ha, a gross annual deforestation rate of 0.048%. Currently, on a national level, post 2000 deforestation area reported in Ireland's NIR is based on changes in land-use of NFI permanent sample plots (Duffy et al., 2014). This sample based

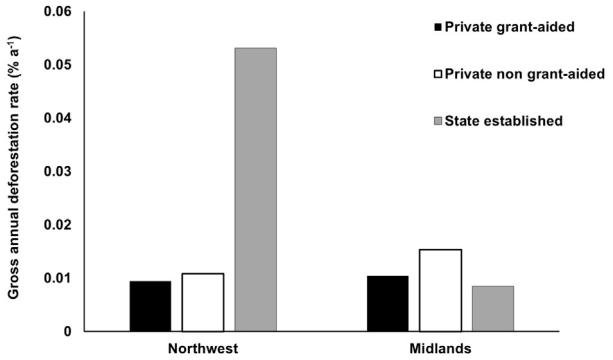

Fig. 8. Gross annual deforestation rate (% a^{-1}) in three pre deforestation ownership categories (private grant-aided, private non grant-aided and state established) in the northwest and midlands study regions.

approach is commonly used in many countries for estimation of deforestation areas (Tomppo et al., 2010). In countries where the deforestation rate is low (<1%), small sample sizes may result in high levels of uncertainty associated with estimates (Dymond et al., 2008; Magnussen, Kurz, Leckie, & Paradine, 2005). In Ireland for example, the NFI derived total national deforestation area for 1998–2006 is 6000 ha ± 3000 ha. The large uncertainty associated with Irelands NFI deforestation estimates is due to the low proportion of deforestation plots in relation to total number of forest plots (0.8%–1.3%) (Forest Service, 2007). In the context of UNFCCC reporting, a key question is whether the true extent of deforestation area falls within NFI deforestation area confidence intervals? Given high accuracies of the Deforestation Map, which combined wall-to-wall PI, official records, and ground survey, it is likely that deforestation estimates derived from this method most closely reflect real world values. During the study period, Deforestation Map estimates for gross annual deforestation (0.048%) are considerably lower than NFI national deforestation rates (0.18%), suggesting that the NFI may overestimate deforestation area. However, our data shows that the rate of deforestation varies regionally, regardless of sampling approach. Therefore, a national study of deforestation area using the Deforestation Map methodology is required to elucidate patterns suggested by this study.

The clear differences in deforestation area as estimated by PI, official records, CORINE and a combined approach are unsurprising given the methodological differences. In both study areas, deforestation area based on official records alone was greatly reduced in comparison to Deforestation Map estimates. These official records are likely to underestimate deforestation area as unlicensed felling activities are unaccounted, as indicated by the low producer's accuracy following accuracy assessment (Table 2).

Certain deforestation activities do not require a felling licence, including some public infrastructural works. This highlights the limitations of using of felling licence data for deforestation estimation. 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. A similar study in Great Britain evaluated deforestation areas estimated by felling licences in comparison to other approaches and concluded that they most likely represented a minimum, as unlicensed felling will also occur but to an unknown extent (Levy & Milne, 2004).

Table 2
Overall, user's and producer's accuracies for deforestation maps derived from photo-interpretation, official records, CORINE, and the Deforestation Map.

Source	Overall Accuracy (%)	User's Accuracy (%)	Producer's Accuracy (%)
Photointerpretation	99.15	100	31.11
Official Records	99.15	93.75	33.33
CORINE	98.70	66.7	8.16
Deforestation Map	99.76	100	80

The semi-automated CORINE approach recorded much lower total deforestation areas in comparison to other methods, along with very low producer's accuracies indicating large omissions of deforested land. This underestimation is likely related to low spatial resolution of CORINE and the size deforestation events in Ireland. For example, 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 8.7 ha. Given the fine-scale nature of deforestation events in Ireland, the 5 ha resolution of the CORINE changes dataset is clearly too large to accurately quantify deforestation areas. A study by Black et al., (Black, O'Brien, Redmond, Barrett, & Twomey, 2008) demonstrated that CORINE data was inappropriate for determining forest related land-use change events in Ireland due to small land parcel sizes. Due to classification errors and low spatial resolution, other studies have highlighted the limitations of using CORINE data for reporting areas under LULUCF (Cruickshank & Tomlinson, 1996; Hazeu & de Wit, 2004). Higher resolution data products, such as the recently launched ALOS PALSAR-2 satellite may be more appropriate for monitoring such small scale events in highly fragmented landscapes with quasi-permanent cloud cover.

Manual interpretation of aerial photography and high resolution optical satellite imagery is a cost-effective tool in determining landscape changes (Morgan, Gergel, & Coops, 2010; Ståhl et al., 2011). In smaller countries, or countries with small forest area, PI may be used to effectively monitor deforestation (DeFries et al., 2007). Using only PI is however subject to limitations such as subjectivity of interpretation and length of time required to manually interpret images. 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-cut/replant silvicultural system. In cases where forest *cover* has been removed, under UNFCCC definitions, clear-cut areas remain in forest *land-use* as long replanting is carried out within a five-year period. In this study, the PI exercise suffered from difficulties of distinguishing clear-felled areas from land-use change areas. Reduced accuracy of the PI approach in comparison to the Deforestation Map was principally due to areas not captured during PI but identified using other data sources, namely bog habitat restoration areas. Such areas are largely indistinguishable from regular clear-felled areas based on imagery interpretation alone. Nevertheless, similar difficulties pertain to fully automated approaches. Given these nuances in regional land-use changes, in this case, a combination of earth observation, national statistics and ground survey is appropriate for quantification of deforestation areas.

4.2. Trends in deforestation land-use transitions

No forest conversions to cropland were identified in either study region. In Ireland, cropland land-use is relatively uncommon, accounting for 5% of the total land area (Forest Service, 2013). Cropland is largely associated with productive agricultural land and generally not considered to be a competing land-use with forest in Ireland and therefore, the lack of deforestation conversions to cropland is unsurprising. Interestingly, a slight decrease in gross annual deforestation rate between 2010 and 2012 was observed in both study regions. One possible reason for this pattern may be a decline in conversions of forest to settlement during the period. The well documented economic

recession in Ireland post 2008 lead to a decline in the construction sector (Whyte, Daly, & Ó Gallachóir, 2013). Based on our research, this is reflected in a decrease in the area of forest converted to settlement during the 2010 to 2012 period.

The higher gross deforestation rate in the northwest is likely related to large-scale bog habitat restoration programmes. Carried out principally in the northwest region, forested areas were clear-cut and returned to their pre-afforestation land-use of wetland. Compared to other recorded deforestation events, these areas were large (>30 ha). Therefore, despite similar densities of deforestation events between the two regions, the higher average size of deforestation events in the northwest for all spatially explicit methodologies is most likely attributable to these bog restoration areas. The higher rate of deforestation of state established forests in the northwest is also attributable to bog restoration activities. Regional differences in the scale of deforestation, and the magnitude of differences between estimation methodologies, highlight the importance of assessing geographically distinct areas to encompass variation in land-use changes.

4.3. Deforestation in different forest types

We assessed the rate of deforestation in three forest type (conifer, mixed, broadleaf) and forest age (<20, 20–40, >40) categories for our study regions. For conifer forests, the highest rate of loss was recorded for the 20–40 years age category. This age interval corresponds with the average rotation time of conifer forests in Ireland. Since 2000, the proliferation of windfarm developments in upland areas where conifer forests are common may have resulted in the higher deforestation rate in this age category. For all forest types, deforestation was lowest in the <20 years age category. Much recent afforestation in Ireland has been planted for the purpose of providing a commercial return via timber harvesting (O'Donnell et al., 2013). The lower proportional deforestation rate in young forests indicates that conversion of forest to other land-uses is less likely prior to commercial maturity. In both regions, the deforestation rate was considerably higher in broadleaf forests in the >60 years age category compared to conifer forests. Broadleaf dominated forests constitute only 25% of the national forest area (Forest Service, 2013). Indeed, semi-natural broadleaf forests are unique in the Irish landscape, accounting for just 2% of the national forest area (Perrin et al., 2008). From a conservation prospective, the higher rate of deforestation of broadleaf forests in comparison to non-native conifer dominated plantation forests is unexpected, particularly in the context on habitat protection legislation such as the EU Habitat Directive. Anecdotal evidence suggests that changes in EU single farm payment subsidies have led to an increase in the conversion of semi-natural forest into agricultural land however empirical evidence linking policy changes with direct land-use conversions is lacking.

5. Conclusions

The forest area in Ireland continues to expand rapidly with 118,000 ha of land afforested between 2000 and 2012. Nevertheless, some recent evidence suggests that the gross national deforestation rate is also increasing (Forest Service, 2013). Overall this study indicated no general increase in deforestation rate during the study period, despite regional variations. Further studies are required to quantify deforestation on a national level to inform UNFCCC and other international reporting requirements. The combination of manual wall-to-wall photointerpretation, official deforestation records and ground survey yielded accurate quantification and characterization of deforestation areas. Where such resources are available, methods outlined here may be used to assess forest related land-use changes, particularly in regions or small countries with fragmented forest cover, rare, fine-scale deforestation events, and where distinguishing between permanent deforestation and forest management (e.g. clear-cutting) is problematic using automated approaches. This study provides a spatially explicit characterization of contemporary deforestation areas and serves as a baseline study of the area and character of 21st century deforested land in Ireland. However, for the purposes of international reporting such as the UNFCCC, yearly updates of national deforestation areas using the Deforestation Map approach may be difficult due to time and cost constraints relating to wall-to-wall manual photo-interpretation and ground survey. Nonetheless, the use of methodologies employed herein can provide a valuable record of forest loss and be used to validate sample-based remotely sensed deforestation estimates.

Acknowledgements

This work was supported by the Science, Technology, Research and Innovation for the Environment (STRIVE) Programme (Grant No. 2011-CCRP-FS-1.1). The programme is financed by the Irish Government under the National Development Plan (NDP) 2007–2013 and is administered by the Environmental Protection Agency (www.epa.ie). The authors would like to thank Ordnance Survey Ireland (OSi) for access to aerial photography (Licence No. EN 0076414). Thanks also to the National Parks and Wildlife Service for provision of National Survey of Native Woodlands data. We are grateful to Coillte Teoranta for providing bog restoration data. Thanks to Brian Barrett, Frank Barrett, Grace Cott and Mark Twomey for assistance with map accuracy assessment.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.apgeog.2015.07.008.

References

Achard, F., DeFries, R., Eva, H., Hansen, M., Mayaux, P., & Stibig, H.-J. (2007). Pan-tropical monitoring of deforestation. *Environmental Research Letters, 2*, 045022.
Ashton, M. S., Tyrrell, M. L., Spalding, D., & Gentry, B. (2012). *Managing forest carbon in a changing climate*. New York: Springer.
Asner, G. P., Powell, G. V., Mascaro, J., Knapp, D. E., Clark, J. K., Jacobson, J., et al. (2010). High-resolution forest carbon stocks and emissions in the Amazon. *Proceedings of the National Academy of Sciences, 107*, 16738–16742.
Black, K., O'Brien, P., Redmond, J., Barrett, F., & Twomey, M. (2008). The extent of recent peatland afforestation in Ireland. *Irish Forestry, 65*, 71–81.
Bonan, G. B. (2008). Forests and climate change: forcings, feedbacks, and the climate benefits of forests. *Science, 320*, 1444–1449.
Bossard, M., Feranec, J., & Otahel, J. (2000). *CORINE land cover technical guide: Addendum 2000*. Copenhagen: European Environment Agency.
Bucha, T., & Stibig, H.-J. (2008). Analysis of MODIS imagery for detection of clear cuts in the boreal forest in north-west Russia. *Remote Sensing of Environment, 112*, 2416–2429.
COFORD. (2009). *Forestry 2030*. Dublin: National Council for Forest Research and Development.
Cross, J. R. (2006). *The potential natural vegetation of Ireland* (pp. 65–116). The Royal Irish Academy.
Cruickshank, M., & Tomlinson, R. (1996). Application of CORINE land cover methodology to the UK-some issues raised from Northern Ireland. *Global Ecology and Biogeography Letters*, 235–248.
DeFries, R., Achard, F., Brown, S., Herold, M., Murdiyarso, D., & Schlamadinger, B. (2007). Earth observations for estimating greenhouse gas emissions from deforestation in developing countries. *Environmental Science & Policy, 10*, 385–394.
Duffy, P., Hanley, E., Hyde, B., O'Brien, P., Ponzi, J., Cotter, E., et al. (2012). *Ireland national inventory report 2013. Greenhouse gas emissions 1990-2011 reported to the United Nations framework convention on climate change* (p. 29). Wexford, Ireland: Environmental Protection Agency.
Duffy, P., Hanley, E., Hyde, B., Ponzi, J., O'Brien, P., Cotter, E., et al. (2014). *Ireland*

national inventory report 2014, greenhouse gas emissions 1990–2012 reported to the united nations framework convention on climate change. Wexford, Ireland: Environmental Protection Agency.
Dymond, J. R., Shepherd, J. D., Arnold, G. C., & Trotter, C. M. (2008). Estimating area of forest change by random sampling of change strata mapped using satellite imagery. *Forest Science, 54*, 475–480.
Eaton, J. M., McGoff, N. M., Byrne, K. A., Leahy, P., & Kiely, G. (2008). Land cover change and soil organic carbon stocks in the Republic of Ireland 1851–2000. *Climatic Change, 91*, 317–334.
Ecke, F., Magnusson, M., & Hörnfeldt, B. (2013). Spatiotemporal changes in the landscape structure of forests in northern Sweden. *Scandinavian Journal of Forest Research, 28*, 651–667.
Falcucci, A., Maiorano, L., & Boitani, L. (2007). Changes in land-use/land-cover patterns in Italy and their implications for biodiversity conservation. *Landscape ecology, 22*, 617–631.
Feranec, J., Hazeu, G., Christensen, S., & Jaffrain, G. (2007). Corine land cover change detection in Europe (case studies of the Netherlands and Slovakia). *Land Use Policy, 24*, 234–247.
Feranec, J., Jaffrain, G., Soukup, T., & Hazeu, G. (2010). Determining changes and flows in European landscapes 1990–2000 using CORINE land cover data. *Applied Geography, 30*, 19–35.
Forest Service. (2007). National forest inventory Republic of Ireland. In *Proceedings of NFI Conference*. Johnstown Castle, Wexford, Ireland: Department of Agriculture, Food and the Marine.
Forest Service. (2013). *Ireland's national forest inventory results 2012*. Johnstown Castle. Co. Wexford, Ireland: Department of Agriculture, Food and the Marine.
Gardiner, M., & Ryan, P. (1969). A new generalised soil map of Ireland and its land-use interpretation. *Irish Journal of Agricultural Research*, 95–109.
Government of Ireland. (1946). *Forestry act*. Dublin: Stationary Office.
Hansen, M., Potapov, P., Moore, R., Hancher, M., Turubanova, S., Tyukavina, A., et al. (2013). High-resolution global maps of 21st-century forest cover change. *Science, 342*, 850–853.
Hansen, M. C., Stehman, S. V., Potapov, P. V., Loveland, T. R., Townshend, J. R., DeFries, R., et al. (2008). Humid tropical forest clearing from 2000 to 2005 quantified by using multitemporal and multiresolution remotely sensed data. *Proceedings of the National Academy of Sciences, 105*, 9439–9444.
Hazeu, G. W., & de Wit, A. J. (2004). CORINE land cover database of the Netherlands: monitoring land cover changes between 1986 and 2000. *EARSeL eProceedings, 3*, 382–387.
Leckie, D. G., Gillis, M. D., & Wulder, M. A. (2002). Deforestation estimation for Canada under the Kyoto Protocol: a design study. *Canadian Journal of Remote Sensing, 28*, 672–678.
Levy, P., & Milne, R. (2004). Estimation of deforestation rates in Great Britain. *Forestry, 77*, 9–16.
Lister, T. W., Lister, A. J., & Alexander, E. (2014). Land use change monitoring in Maryland using a probabilistic sample and rapid photointerpretation. *Applied Geography, 51*, 1–7.
Lydon, K., & Smith, G. (2014). *CORINE land cover 2012 Ireland final report*. Johnstown Castle, Wexford: Environmental Protection Agency.
Magnussen, S., Kurz, W., Leckie, D. G., & Paradine, D. (2005). Adaptive cluster sampling for estimation of deforestation rates. *European Journal of Forest Research, 124*, 207–220.
Magnussen, S., & Russo, G. (2012). Uncertainty in photo-interpreted forest inventory variables and effects on estimates of error in Canada's national forest inventory. *The Forestry Chronicle, 88*, 439–447.
Mitchell, F. (2000). The development of Ireland's tree cover over the millennia. *Irish Forestry, 57*, 38–46.
Morgan, J. L., Gergel, S. E., & Coops, N. C. (2010). Aerial photography: a rapidly evolving tool for ecological management. *BioScience, 60*, 47–59.
Nowak, D. J., & Greenfield, E. J. (2010). Evaluating the National Land Cover Database tree canopy and impervious cover estimates across the conterminous United States: a comparison with photo-interpreted estimates. *Environmental Management, 46*, 378–390.
Nowak, D. J., & Greenfield, E. J. (2012). Tree and impervious cover change in US cities. *Urban Forestry & Urban Greening, 11*, 21–30.
Olofsson, P., Foody, G. M., Herold, M., & Stehman, S. V. (2014). Good practices for estimating area and assessing accuracy of land change. *Remote Sensing of Environment, 148*, 42–57.
O'Donnell, A., Cummins, M., & Byrne, K. A. (2013). Forestry in the Republic of Ireland: government policy, grant incentives and carbon sequestration value. *Land Use Policy, 35*, 16–23.
Penman, J., Gytarsky, M., Hiraishi, T., Krug, T., Kruger, D., Pipatti, R., et al. (2003). *Good practice guidance for land use, land-use change and forestry*. Institute for Global Environmental Strategies.
Perrin, P., Martin, J., Barron, S., O'Neill, F., McNutt, K., & Delaney, A. (2008). *National survey of native woodlands 2003-2008* (volume i). Dublin: National Parks & Wildlife Service. Main report.
Pettorelli, N., Vik, J. O., Mysterud, A., Gaillard, J.-M., Tucker, C. J., & Stenseth, N. (2005). Using the satellite-derived NDVI to assess ecological responses to environmental change. *Trends in ecology & evolution, 20*, 503–510.
Portillo-Quintero, C., Sanchez, A., Valbuena, C., Gonzalez, Y., & Larreal, J. (2012). Forest cover and deforestation patterns in the Northern Andes (Lake Maracaibo Basin): a synoptic assessment using MODIS and Landsat imagery. *Applied Geography, 35*, 152–163.
Potapov, P. V., Turubanova, S. A., Hansen, M. C., Adusei, B., Broich, M., et al. (2012). Quantifying forest cover loss in Democratic Republic of the Congo, 2000–2010, with Landsat ETM+ data. *Remote Sensing of Environment, 122*, 106–116.
Ståhl, G., Allard, A., Esseen, P.-A., Glimskär, A., Ringvall, A., Svensson, J., et al. (2011). National Inventory of Landscapes in Sweden (NILS)—scope, design, and experiences from establishing a multiscale biodiversity monitoring system. *Environmental Monitoring and Assessment, 173*, 579–595.
Tomppo, E., Gschwantner, M., Lawrence, M., & McRoberts, R. E. (2010). *National forest inventories pathways for common reporting*. Dordrecht: Springer.
Turner, W., Spector, S., Gardiner, N., Fladeland, M., Sterling, E., & Steiniger, M. (2003). Remote sensing for biodiversity science and conservation. *Trends in Ecology and Evolution, 18*, 306–314.
UNFCCC. (1992). *United Nations Framework convention on climate change*. http://unfccc.int/.
UNFCCC. (1997). *Kyoto Protocol to the United Nation Framework convention on climate change*. http://unfccc.int/.
Van der Werf, G. R., Morton, D. C., DeFries, R. S., Olivier, J. G., Kasibhatla, P. S., Jackson, R. B., et al. (2009). CO_2 emissions from forest loss. *Nature Geoscience, 2*, 737–738.
Whyte, K., Daly, H. E., & Ó Gallachóir, B. P. (2013). Modelling HGV freight transport energy demand in Ireland and the impacts of the property construction bubble. *Energy, 50*, 245–251.
Zhao, B., Kreuter, U., Li, B., Ma, Z., Chen, J., Nakagoshi, N., et al. (2004). An ecosystem service value assessment of land-use change on Chongming Island, China. *Land Use Policy, 21*, 139–148.