A rapid assessment using remote sensing of windblow damage in Irish forests following Storm Darwin

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Abstract

A National Windblow Task Force was set up following the catastrophic windstorm in February 2014. Part of the Task Force's work was to conduct a rapid assessment of wind damage to Irish forests across the Estate (both public and private). The RapidEye satellite constellation was chosen for the acquisition of post-storm image data as it was the most cost effective and flexible data source to map the spatial extent of the wind damage in Irish forests (both public and private). The satellite image data were analysed using a supervised classification. Vegetation indices and textural features were used to assist in the classification. The digital wind damage map generated by the consortium, demonstrated the effective use of remote-sensing for the collection of windstorm forest damage data in Ireland. Within 8 weeks of data delivery, the consortium concluded that at that time, over 8,000 ha of forests were damaged by the storm, approximately 6,000 ha of state forests managed by Coillte Teoranta and a further 2,000 ha forest held in private ownership.

Keywords: *Wind damage, optical remote sensing, vegetation indices.*

Introduction

Background

Windblow refers to the uprooting or breakage of trees by wind. Windblow results when the wind-induced drag force on the tree crown, multiplied over the lever-arm of the stem, results in a turning moment that exceeds the bending resistance of the stem, or the root anchorage (Mitchell 2013). In terms of volume loss, wind is the most important disturbance agent in European forest ecosystems (Gardiner et al. 2010). However, in Ireland, volume loss to wind damage is of more significance. Given the country's geographical position, it is subjected to more intense cyclones, extreme gales and precipitation when compared to other European countries. Historical climatic records for the period 1947-1974 (Gallagher 1974) indicate that our climatic conditions will result in extensive recurrent windblow or endemic windblow - with severe wind storms occurring at 10-15 year intervals, and sometimes more frequently resulting in catastrophic wind damage. Ní Dhubháin (1998) reported that an estimated

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85,000 m^3 of timber are blown over annually in this country based on data collected for State and Coillte Teoranta (Coillte) forest between 1980 and 1997. However, more recent Coillte records show annual average invoicing levels for windthrow material of 241,000 m^3 over the 24 years between 1992 and 2015 (Anon 2016). Considering the national private estate amounts to approximately 47% of the forest area of Ireland (DAFM 2013) and the large area of grant-aided private planting which took place in the 1990's is now reaching maturity, the total national annual volume lost to wind damage is likely to be significantly higher.

Sustained winds (>10 minutes), as opposed to gusts, above storm force 10 are relatively rare in Ireland. Violent storm force 11 sustained winds, have only been recorded on four occasions since 1940 at Met Éireann's Valentia Observatory (McGrath 2015). The last occurrence of storm force 11 was in February 2014 and was associated with Storm Darwin.

Storm Darwin

Between the 5th of December 2013 and the 12th of February 2014, storm force winds occurred on 12 separate days. This series of storms led to a large increase in rainfall throughout the country on soils which were already heavily saturated. The most severe event, named Storm Darwin, occurred on the 12th of February 2014 and was associated with an active depression off the south coast that tracked steadily north eastwards over the country. Figure 1 shows an image captured by NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) of Storm Darwin above Ireland. Cork Airport and Valentia Observatory reported their highest mean wind speeds in 17 years, while Shannon Airport recorded the month's highest gust of 159 km/h, its highest gust for February since records began in 1946.

From the perspective of sustainable forest management, storm damage can have an immediate catastrophic effect: uprooting and snapping trees at mid-height, blocking roads, bringing down electric power lines and creating serious safety hazards. In the medium term, tree clearance needs to take place before the downed timber begins to degrade; also administrative and legal requirements in regard to felling must be considered; harvesting equipment deployed, road access provided and marketing of the timber quickly progressed. As 47% of Ireland's forest area is now spread across many thousands of sometimes inexperienced private owners, a coordinated response was needed after Storm Darwin to support post-storm forest management, felling licence control and post-hazard relief activities.

In the immediate aftermath of storm Darwin, Mr. Tom Hayes T.D., Minister for State for Forestry at the Dept. of Agriculture, established a Task Force to respond to the catastrophic effects the storm had on Irish forests. A requirement to map and estimate the area and volume of wind damage in both public and private forests was

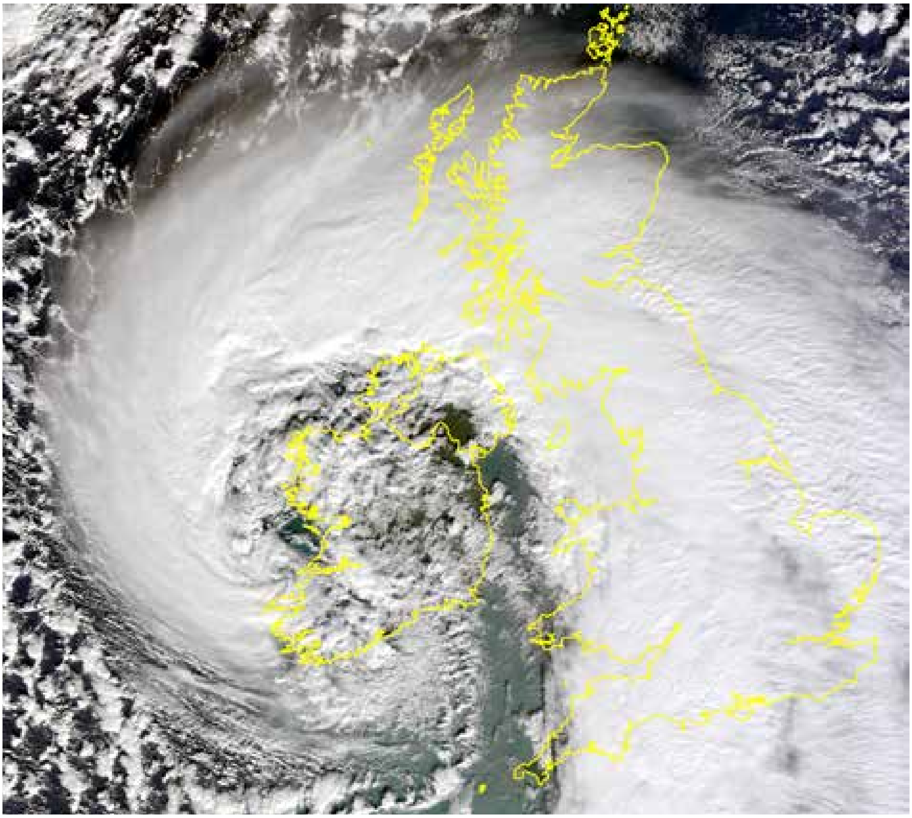

Figure 1: *NASA Earth Observatory image by Jesse Allen, using data from the Land-Atmosphere near real-time capability for EOS (LANCE). Image acquired 12th February 2014. Availabe at http://earthobservatory.nasa.gov/NaturalHazards/view.php?id=83127.*

identified by the Task Force members. A range of data sources and methodologies were reviewed by the Task Force that included field inventory and mapping; aerial photography; airborne laser scanning data and optical satellite imagery. Although the strength of the storm was fully apparent, it was still unknown which areas had been hardest hit. It was therefore essential to utilise data that provided a synoptic view of

Table 1: *Invoiced volumes (000s m^3) from Coillte windblow sales proposals (1992-2015).*

Year	Invoice sales	Year	Invoice sales	Year	Invoice sales
1992	246	2000	921	2008	67
1993	198	2001	387	2009	54
1994	237	2002	234	2010	77
1995	184	2003	113	2011	43
1996	92	2004	66	2012	53
1997	57	2005	54	2013	42
1998	356	2006	52	2014	379
1999	894	2007	56	2015	920

the forests, that could be acquired quickly and cost-effectively and used as the basis for a rapid, reliable, objective and semi-automated approach to damage detection.

In Coillte, as can be seen from Table 1, the sale of windblown timber has been characterised by a managed release following each storm event with a view to protecting the market for public and private timber by reducing the risk of over-supply adversely affecting price. Only when the full scale of the damage is known can this type of strategic action take place. In addition to strategic actions related to the supply of windblown timber to the market, the collection and study of windstorm damage information is critical for the understanding of wind effects on forests. Satellite remote sensors can provide the required information in a timely and reliable way.

Remote sensing for windblow damage assessment

Earth observation data has been widely used to rapidly detect disturbances and damage to forests at a variety of spatial scales. Space-borne satellite imagery is well suited for these tasks as new images are regularly acquired and the synoptic view offered by satellite data facilitates large area assessments. For instance, the European Forest Fire Information System (EFFIS) uses daily updated satellite data to identify and map wildfire and forest damage across Europe (Sedano et al. 2012). Similarly, satellite data has been used to quantify the extent of windstorm in forests. Wind damage can be analysed and assessed over large areas in a timely and cost effective manner by using satellite sensor imagery in combination with spatial analysis as provided by Geographical Information Systems (GIS). Nelson et al. (2009) combined Landsat data and stand inventory records from the Forest Inventory and Analysis (FIA) program to assess the effects of a catastrophic windblow event in northern Minnesota, USA and achieved an overall accuracy of 90% of the image-based damage classification map product. In addition, they provided estimates of total volume that was lost during the storm event. Jonikavičius and Mozgeris (2013) applied a similar approach using multi-temporal Landsat imagery, stand-wise forest inventory and a k-NN estimator to assess forest damage in Lithuania following a storm that occurred in August 2010.

In Europe, there has been extensive research into remote sensing techniques to assess the effects of the 2009 windstorm Klaus. Kempeneers et al. (2012) used low resolution, MODIS satellite data and a post-classification method to quantify the extent of windstorm damage in the Landes region of France. The same storm and study area was researched by Chehata et al. (2014), who applied a feature-selection and an image segmentation algorithm to high resolution, multi-spectral satellite imagery from Formosat-2 for the purposes of mapping the extent of the wind damage in the pine forests.

Aerial photography surveys tend to provide high levels of spatial detail, but they are typically not immediately available in the aftermath of a storm for large areas. However, when available, they are used for detailed windblow damage detection and assessment.

For instance, windblow gaps were detected by Jackson et al. (2000) from a multi-band Airborne Thematic Mapper (ATM) and a pixel-based maximum likelihood classifier. The approach successfully mapped forests, moorland and windblow gaps in Central Wales with an overall accuracy of 90%. Honkavaara et al. (2013) generated a post-storm Digital Surface Model (DSM) from high-flown orthophotographs in conjunction with a pre-storm LiDAR derived DSM to automatically map wind damage in Finnish forests.

Objectives

The aim of the rapid damage assessment defined by the Windblow Task Force was to better understand and quantify the wind damage affecting Irish forests and thereby improve decision making and support post-storm forest management. More specifically, the objectives of the rapid damage assessment were to:

1. estimate the extent and area of wind damage in Irish forests in the aftermath of Storm Darwin;
2. provide up-to-date, accurate spatial information that can assist decision makers in formulating relevant policies and aid forest companies with strategic planning. Information generated would aid forest managers/owners with, felling licence preparation, post-hazard relief activities and subsequent silvicultural management;
3. develop cost-efficient and reliable and highly automated methods that can assist the analysis in a timely fashion.

Materials and methods

Study area

While climatic records suggest that Storm Darwin was broadly a 1 in 20 year event, the categorisation as "worst in living memory" may be appropriate in the worst affected areas (McGrath 2015). The frequency and ferocity of the 2014 storm events, compounded by waterlogged soils on many sites, lead to extensive windblow. While initial estimates put the area damaged at less than 1% of the total forest area, locally the damage was severe, with significant volumes of roundwood impacted. The most severe Storm Darwin wind and associated forest wind damage was experienced in Galway, Clare, Limerick, Kerry and Cork but also included coastal areas in the south and northwest. Preliminary assessments of the damage immediately after the storm by the Windblow Task Force produced only a rough estimate of the amount and spatial location of damaged stands. It was estimated that area of wind damaged forest amounted to approximately 8,000 ha with the main concentration of damage occurring in Munster and south Leinster (Figure 2). The extreme west to northwest gusty winds behind the storm centre caused the majority of windblow. The strong gales and damage was also notable in regions around the M7 motorway corridor from Limerick to Dublin.

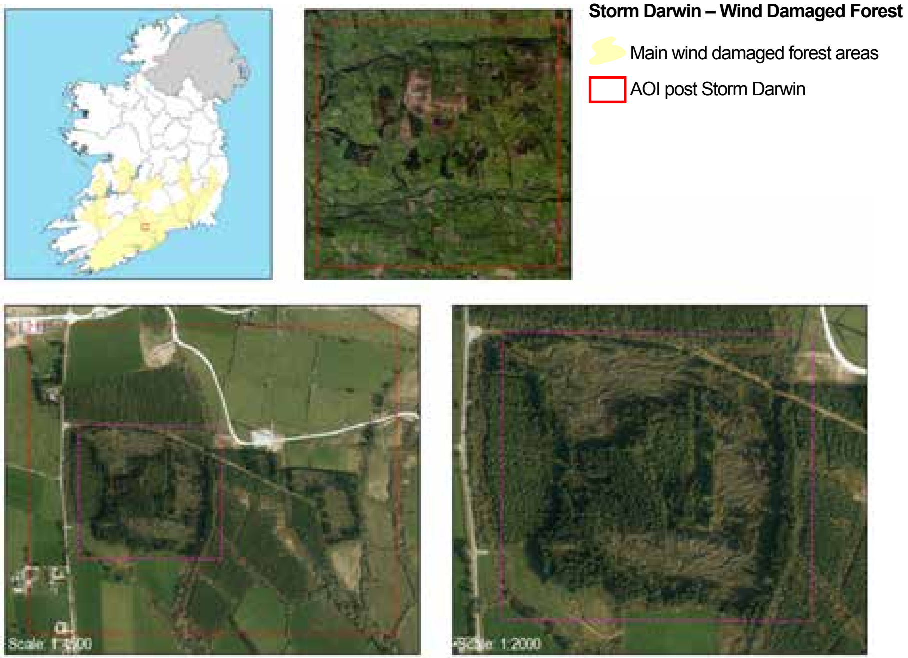

Figure 2: *Figure 2 Overview of main wind damaged forest areas following Storm Darwin with an example of post storm event forest damage near Ballyduff, (orthophoto 21st/22nd April, 2014, © BlueSky/Ordnance Survey Ireland).*

Data

Given the fact that there are many options that could potentially be used for the purposes of mapping the wind damage, it was necessary to identify data sources that could be realistically acquired within the time-frame of the project, available budget and meet the technical specifications. In the immediate aftermath of the storm, a number of data sources were critically evaluated based on the following criteria:

1. the feasibility to rapidly acquire data across the entire island;
2. quality of the data in terms of spatial resolution (image detail) and spectral resolution (information content);
3. total cost per unit area; and
4. health and safety considerations.

Aerial photography and Airborne Laser Scanning/LiDAR data would have been the optimal choice for detailed mapping, but they would have been too expensive for national coverage and it would have been unrealistic to acquire the data within the time-frame. Similarly, data acquired from Unmanned Airborne Vehicles (UAVs/

drones) would have provided imagery with high spatial resolution, but the cost and time in acquiring data across the country would have been prohibitive.

Space-borne satellite imagery was therefore considered as the most viable option for the purposes of the project.. A thorough evaluation of satellite data products were evaluated for the purposes of the project, which included Landsat, SPOT, Disaster Monitoring Constellation (DMC) and Indian Remote Sensing (IRS). The criteria that were used during the evaluation focussed on likelihood of cloud-free image data capture, cost, sensor specifications to meet the project requirements and availability of post-storm sample imagery. It was concluded that satellite sensors that form part of constellations and have the ability to be pointed are more suited in these instances. Consequently, the RapidEye constellation was identified as the most suitable data source in terms of:

1. image data quality - spectral resolution and spatial resolutions;
2. cost per unit area, and;
3. flexibility in terms of data acquisition.

This latter point is particularly pertinent to Ireland, where cloud-cover hampers the operational use of space-borne satellite data from sensors that are in fixed orbit. The ability of RapidEye to "tilt and point" in order to capture imagery increases the chances of acquiring cloud-free data.

RapidEye

The RapidEye system is a constellation of five identical space-borne sensors that are operated by Planet (previously known as Planet Labs/Blackbridge). The five satellites are located in a sun-synchronous orbit at 630 km. The sensors capture image data across the five following spectral bands:

- blue (440 – 510 nm)
- green (520 – 590 nm)
- red (630 – 685 nm)
- red edge (690 – 730 nm)
- near infra-red (760 – 850 nm)

The satellite's image pixel size is 5 m and each image tile is 25 × 25 km representing an area of 625 km^2. Each satellite sensor revisits the same location on the Earth's surface every 5 days, but RapidEye has the added flexibility of being capable of being programmed to tilt and capture data off its orbit. This unique benefit permitted data to be captured during cloud-free periods in April 2014. A subset of a RapidEye satellite image scene acquired over County Clare is provided in Figure 3. The cost of each image tile was €625, which is equivalent to €0.01 ha^{-1}.

Figure 3: *False-colour composite RapidEye satellite image acquired over Slieve Aughties, Co. Clare.*

Aerial photography

Three additional aerial datasets were used as part of the rapid damage assessment and specifically the quality assurance/quality control aspects of the analysis. These included: (1) aerial photography acquired by Ordnance Survey Ireland (OSi) during the period of April 2014 in the area of Rockchapel covering an extent of 40 km^2; (2) Digital Globe (Bing) aerial photography acquired between 2011-2013 accessed via a Web Map Service (WMS); (3) Coillte reconnaissance flight surveys over key areas considered to be affected by the storm. This latter dataset was used in conjunction with field inventory and verification subsequently digitally mapped by the Coillte GIS team.

Forest vector databases

The Forest Service's Forestry12 vector database and Coillte's Sub-compartment database were both used in this analysis. The Forestry12 dataset was used to mask the satellite imagery and to remove all satellite image pixels that were outside of the vector database. This reduced the computational area and image processing time quite significantly and ensured that analysis was focussed on only public and privately owned forests.

Methods

For the purposes of the project, it was agreed by the Ministerial Task Force that catastrophic wind damage would be assessed and quantified from the satellite data. In the context of this project, catastrophic wind damage related to gaps that were greater than 0.5 ha and where the trees were levelled. The project did not seek to map single tree damage or gaps smaller than 0.5 ha, or areas where there was partial blow (i.e. trees were still standing at an angle of 45 degrees). Furthermore, it did not map areas that would have been included as part of a forest management felling prescription, i.e. "squaring off" areas.

The processing and analysis of the RapidEye satellite data was carried out on a Workstation running Linux (Ubuntu 12.04 LTS) using free, open-source geospatial tools that included:

- the Geospatial Data Abstraction Library (GDAL) (http://gdal.org) that was used for the pre-processing of satellite imagery and vector datasets (e.g. coordinate transformation, image masking);
- Orfeo Toolbox (OTB) for the calculation of textural image features and vegetation indices;
- pktools (http://pktools.nongnu.org) was used for the supervised image classification using a Support Vector Machine (SVM), accuracy assessment and post-processing of the image classification (sieving and filtering);
- QGIS (http://qgis.org) was used for the visualisation and interpretation of image and vector datasets as well as for map production and analysis;
- R Statistics (http://r-project.org) was used for statistics and reporting.

In total, 224 individual image scenes were acquired for the project; in some instances, if the cloud cover was too high, multiple image scenes were delivered by the data providers for the same area. Given the number of scenes involved, a semi-automated processing workflow was developed as a Unix shell script to facilitate the processing within the given timeframe. Figure 4 provides an overview of the processing workflow that covers the pre-processing, image classification and quality control of the output products.

For the purposes of this project, the RapidEye Level-3A products were used, which are ortho-rectified tile products and have radiometric, geometric and terrain corrections. The images were all ortho-rectified by Planet (Blackbridge) using the Landsat-7 GCP model (Personal communication, 2014). Consequently, no further changes to the image geometry were carried out as part of the pre-processing steps. Furthermore, given the strict timelines, the images were not atmospherically corrected and as such the Digital Numbers were used for the analysis. Overall, the RapidEye imagery achieved a cloud cover of less than 20%. In cases where this was exceeded, a

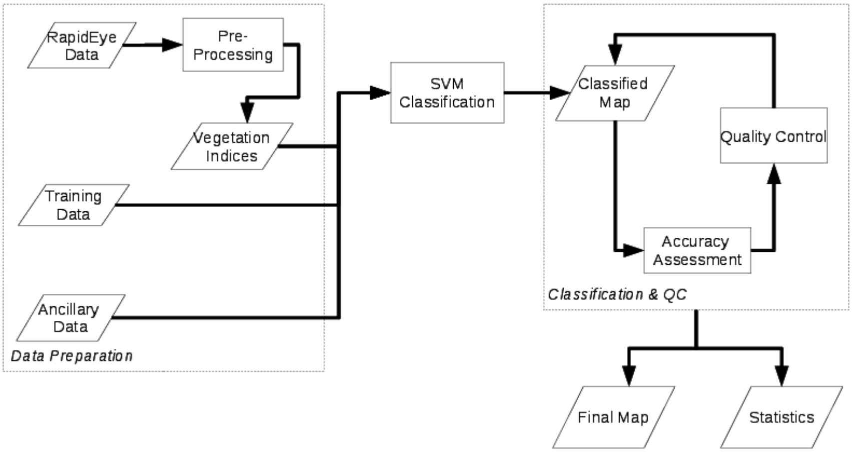

Figure 4: *Windblow rapid damage assessment workflow.*

subsequent satellite image scene was delivered of the affected area. For the purposes of the analysis, a cloud mask (including haze) was generated by photo-interpretation in conjunction with the Unusable Data Mask (UDM) file provided with the Level-3A product.

A number of image features were generated from the satellite data that were used as explanatory variables to improve the discrimination between damage classes. These included the:

- Normalised Difference Vegetation Index (NDVI), which is defined as a ratio between the Near Infra-Red (NIR) and Red (R) spectral bands :
  NDVI = (NIR – R) / (NIR + R) ;
- Normalised Difference Red-Edge Index (NDRE) is similar to the NDVI, but instead of using the NIR it relies on the Red-Edge band:
  NDRE = (RE – R) / (RE + R);
- a set of Haralick Textural features including entropy and standard deviations (Haralick et al. 1973).

It should be noted that the vegetation indices follow a phenological pattern and that the dates of the acquired RapidEye data did not correspond with the peak of the growing season. This may have resulted in a relatively less accurate classification than would have been the case had the RapidEye data been acquired in May or June. However, a pragmatic decision was made to use these indices in the context of the analysis as they can nonetheless be used to discriminate between stands affected by windblow from those that were not; that being the purpose of the exercise, rather than the calculation of NDVI or NDRE for the purposes of phonological analysis.

As such, the explanatory variables for the image classifier consisted of the five spectral bands from the RapidEye data, two Vegetation Indices (NDVI/NDRE) and two Haralick features (standard deviation and entropy). This set of variables formed the input data for the supervised image classifier that was implemented using a Support Vector Machine (SVM) from the pktools packages (McInerney and Kempeneers 2014). A SVM classifier is a supervised machine learning algorithm that can be used for image classification. SVM classifiers have their roots in Statistical Learning Theory and have gained prominence because they are robust, accurate and are effective even when using a small training sample (Gidudu et al. 2007). They are non-parametric and therefore no *a priori* assumptions are made about the distribution of the probability density functions of each each class. SVMs are based on the idea of finding the optimal hyperlane (line) that gives the best separation between two classes in a training dataset (Hastie et al. 2001). The image classification was defined to include two classes:

- standing (un-damaged forests),
- wind damaged forests.

Supervised classifiers require a "reference dataset" that consists of a number of training sites that are considered to be representative of each class. These training sites are manually photo-interpreted and digitised across the image and then the spectral signature (spectral information from the satellite imagery) is extracted for each labelled training site. The image classifier uses these training features to identify and classify the satellite image based on the spectral information.

The image classifier produced an intermediate product, which was cross-checked as part of a quality control process, with Bing/Digital Globe aerial photography. This process was necessary in the absence of pre-storm RapidEye data and provided a facility to determine if a change had occurred or not during the intervening period.

Results

The results from the automated mapping highlighted areas that were most severely hit included areas of Counties Kerry, west Cork, Limerick, Tipperary and Clare. A heat-map was generated from the damage dataset that provided an overview of the damage across Ireland. Examples of the mapped output is provided in Figure 5 for areas that were windblown in Co. Clare. The delineation is based on a vectorisation of the raster classification, which produces the step-like boundary. Generalisation algorithms can be applied to produce a smoothed linear boundary.

Accuracy Assessment

The confusion (error) matrix for the image classification based on a random sample of points generated within the extents of the OSi aerial photography in Co. Limerick

Figure 5: *Automatic delineation of windblow damage from RapidEye satellite imagery.*

(Table 2). Each point represented the centre of a synthetic 0.04 ha plot, which was photo interpreted in a GIS. The Digital Globe orthophoto dataset used reflected the pre-storm situation and was used for comparison purposes in the areas coinciding with the OSi orthophotography. The synthetic plots were based on the interpretation of a 4 × 4 window of pixels around the point. The class assigned to the point (synthetic plot) was based on the majority of the class interpreted from the aerial photography. This approach alleviated the issues associated with the difficulty in interpreting single points that occur on boundaries. The validation dataset (n = 262) was then compared to the output of the image classification to provide an overall accuracy of the classification

Table 2: *Error matrix based on classification output (forest area in ha).*

		Reference	
	Undamaged	**Damaged**	**Total**
Undamaged	193	6	189
Damaged	26	37	63
Total	219	43	262
Overall accuracy		83.33 (+/- 2.7)	

	Undamaged	**Damaged**
Producer' accuracy	88.12 (±3.14)	86.05 (±10)
User's accuracy	96.83 (±1.48)	59.00 (±9.63)
Kappa Index of Agreement	68%	

output and a producer's and user's accuracies. The producer's accuracy (PA) refers to the omission estimates, while the user's accuracy refers to the commission estimates.

The overall accuracy of the rapid damage assessment dataset based on the study area in Athea, Co. Limerick was 83.3%. The producer's accuracy for the undamaged and damaged classes were 88 and 86% respectively, while the user's accuracy (commission errors) were lower for the damage class at 59%. These commission errors were largely attributed to miss-classifications due to cloud-shadow, shadows cast by trees due to low sun-angles and existing gaps within the forest. Validation was not considered for the remainder of the country because of tight project timelines for completion of the project. In addition, Co. Limerick was representative of the damage experienced in other countries. Subsequent wind damage field surveys and site level damage mapping by Coillte showed that his was the case on the ground.

Summary statistics

A summary of the wind damage mapped by county is provided in Table 3. It is evident from the table that the majority of the damage occurred in the public forests (Coillte forest area) with Counties Clare, Cork, Limerick and Kerry most severely hit, which is also illustrated by the heatmap of wind damage across the country (Figure 6).

Table 3: *Cumulative windblow damage by county for public and private forests as detected from the Rapid Damage Assessment.*

County	Forest area (ha)	Damage private (ha)	Damage public (ha)	Percentage
Clare	52,000	579	884	2.81
Cork	83,000	364	1,572	2.33
Cavan	16,000	0	14	0.09
Carlow	8,000	3	101	1.30
Donegal	56,000	5	56	0.11
Galway	59,000	56	114	0.29
Kilkenny	19,000	72	268	1.79
Kerry	53,000	501	944	2.73
Longford	8,000	0	2	0.03
Leitrim	25,000	1	12	0.05
Limerick	26,000	354	958	5.05
Laois	25,000	14	93	0.43
Mayo	51,000	4	17	0.04
Offaly	24,000	0	6	0.03
Sligo	20,000	1	15	0.08
Tipperary	48,000	232	552	1.63
Waterford	26,000	8	179	0.72
Wicklow	35,000	2	66	0.19
Wexford	13,000	2	269	2.08
Total	**647,000**	**2,198**	**6,122**	**1.29**

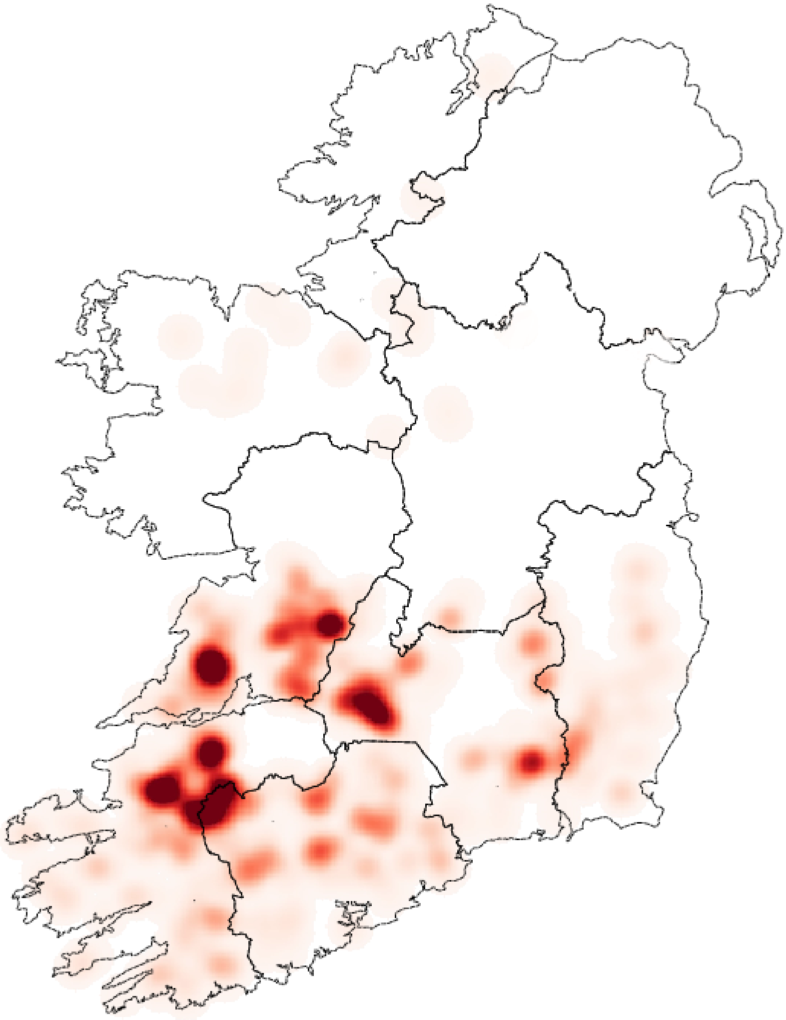

Figure 6: *Heat map of wind damage across the estate. Darker red indicates more intense damage.*

Discussion

Quantification of spatial and temporal changes in forest cover is an essential component of forest monitoring programs and space borne passive optical or NIR remote sensing has been an important tool for mapping the extent and location of large-scale forest disturbances. However, frequent extensive cloud cover over mid-latitude coastal regions of the Northern Hemisphere, such as Ireland, has historically presented a challenge to optical remote sensing of these areas (O'Connor et al. 2008, Serbin and Green 2015). The 5-satellite RapidEye constellation provided the required earth observation data in a flexible, timely and reliable way and showed the utility of accessing a multiple sensor constellation service for operational use at a latitude where almost year round cloud cover and long-time satellite revisit times has historically been a barrier to national scale remote sensing initiatives.

The delivery of a national Irish wind damage map product after only a 12-week period is testament to the operational viability of the approach and demonstrates that wind damage can be analysed and assessed over large areas in a timely and cost effective manner by using satellite sensor imagery in combination with spatial analysis as provided by Geographical Information Systems (GIS). The digital wind damage maps of windblown areas are currently available on the industry mapping system (iNET) provided by the Forest Service in the Department of Agriculture, Food and the Marine to registered foresters operating the Department's Schemes. This national wind damage "map layer" provides forest managers, owners, and the Forest Service with much needed information for forest management planning, harvest scheduling, timber processing, reforestation and the regulation of felling activities.

A damage classification of wind damaged forest was not considered for the work undertaken by the consortium. Damage classification typically requires assignment of a continuous damage measure into discrete damage classes (e.g. Olthof et al. 2004, Jonikavičius and Mozgeris 2013). In the context of this rapid damage assessment, wind damage was defined as gaps in the canopy cover greater than 0.5 ha and where the trees were levelled. The project did not seek to map single tree damage or gaps smaller than 0.5 ha, or areas where there was partial blow (i.e. trees were still standing at an angle of 45 degrees). In future, it would be of benefit to identify those areas where partial blow is also present and classify the degree of wind damage so that a more comprehensive estimate of wind damaged areas might be produced.

Copernicus Emergency Management Service (© European Union 2016) (EMS) provides information for emergency response in relation to different types of disasters, including meteorological hazards, geophysical hazards, deliberate and accidental man-made disasters. Copernicus EMS consists of the Mapping Service and of the Early Warning System (floods). Contact with Copernicus was initiated as part of the Task Force response to the wind damage caused by storm Darwin. Wind damage maps and data products were subsequently provided by Copernicus for three 10 km^2 areas centred around Templeglantine, Co. Limerick and Kilmaley, Co. Clare (Copernicus Emergency Management Service (© European Union 2014, EMSR077) to the Forest Service in the Department of Agriculture, Food and the Marine (DAFM). The products from the Copernicus EMS were useful in demonstrating the capacity of earth observation data to identify and quantify areas of wind damage in a short time frame and facilitated verification of at least some of the felling licence applications to the Forest Service for wind damage within the mapped areas. Unfortunately, the Copernicus EMS could not meet the basic requirement for a nationally consistent wind damage assessment product and so the decision was made by the consortium to proceed with RapidEye damage assessment as carried out by Coillte.

Increasing storm intensity accompanied by heavier rainfall leading to more saturated soils together with an increasing and ageing forest stock are expected to result in substantial increases (at least double) in forest damage across Europe by the end of the century (Gardiner et al. 2010). Climatic simulations carried out by Gleeson et al. (2013) for Ireland showed an overall increase (0 to 8%) in the energy content of the wind for the future winter months and a decrease (4 to 14%) during the summer months. A recent study with a very high resolution version of the EC-Earth model (Haarsma et al. 2013) also suggests an increase in the frequency of extreme wind storms affecting Western Europe in future autumn seasons due to global warming. This will translate into an increased risk of storm damage, flooding and soil saturation with associated risk of damage to Irish forests.

There is no consistent recording and reporting system for wind damage across Europe or for reporting damage from different hazards. This leads to uncertainties in relative levels of wind damage within different parts of Europe and in comparing the importance of hazards (Gardiner et al. 2010). The Forest Service (DAFM) are currently members of the European Horizon 2020 funded DIABOLO project which will provide improved information related to forest disturbances (e.g. forest fires, storm, drought, insect outbreaks) and their impacts using earth observation data. Working Group 4 of the DIABOLO project aims to provide European scale harmonised data on forest disturbances and also a near real time forest disturbance monitoring service via a European Forest Disturbance Monitoring System (EFDMS). The experience and lessons learned from the Rapid Damage Assessment of Windblow post storm Darwin will help to steer and improve the design, development and methodology implemented for the EFDMS, making its application more relevant in an Irish context. In addition, by adoption of a test site in Ireland, DIABOLO will further strengthen the capacity for both assessing risks and monitoring forest disturbances such as wind damage on a pan-European scale and at regional levels.

Conclusion

It has been well established that space borne passive optical or NIR remote sensing is an important tool for mapping the extent and location of forest disturbances. The results of this study demonstrate the applicability of remote sensing data in collecting windstorm forest damage data in Ireland. A reliable, objective, digital methodology for forest change detection using RapidEye imagery was developed and applied successfully in an Irish forest context. The supervised classification, vegetation indices (NDVI/NDRE) and textural analysis methods adopted were well suited for emergency mapping and allowed for accurate and timely assessment of windstorm damage, meeting the objective of windblow Task Force in terms of identifying damage locations.

The 5-satellite RapidEye constellation provided the required image data in a flexible, timely and reliable way. It demonstrated the benefit of accessing a multiple sensor constellation service for operational use at a latitude and during a season where high cloud cover has historically been a barrier to national scale remote sensing surveys. Employing an open source and highly automated remote sensing methodology was particularly effective given the short timeframe to produce the national windblow map data, which would not have been possible with the sole use of a ground-survey.

The DAFM experience with Copernicus EMS has shown that while it is not applicable for national scale surveys, the service will be of significant future value in cases of localised forest damage and or related emergencies (e.g. upland fires/forest fires or localised wind damage).

Finally, the spatial data generated in the national wind damage map can be used in a research context and over the longer term in policy development for improved forest management, improved forest design (e.g. cultivation practices, species choice) and damage mitigation measures to increase the resilience of Irish forests to future storms.

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References

Anon. 2016. Coillte invoiced sales volumes from windthrow sales proposal 1992–2015. Unpublished.

Chehata, N., Orny, C., Boukir, S., Guyon, D. and Wigneron, J.P. 2014. Object-based change detection in wind storm-damaged forest using high-resolution multispectral images. *International Journal of Remote Sensing* 35: 4758–4777.

Copernicus Emergency Management Service. 2014. EMSR077. Available at http://emergency.copernicus.eu/EMSR077 [Retrieved September 2015].

DAFM. 2013. *National Forest Inventory – Republic of Ireland – Results. Covering the National Forest Inventory, 2009 to 2012*. Johnstown Castle, Co. Wexford. pp. 265.

Gallagher, G.J. 1974. Windthrow in state forests in the Republic of Ireland. *Irish Forestry* 31: 154–167.

Gardiner, B., Blennow, K., Carnus, J.M., Fleischner, P., Ingemarson, F., Landmann, G., Lindner, M., Marzano, M., Nicoll, B., Orazio, C., Peyron, J.L., Reviron, M.P., Schelhaas, M., Schuck, A., Spielmann, M. and Usbeck, T. 2010. *Destructive storms in European Forests: Past and Forthcoming Impacts*. Final report to European Commission - DG Environment. European Forest Institute, Joensuu, Finland. p. 138.

Gidudu, A., Hulley, G. and Marwala, T. 2007. *Classification of Images using Support Vector Machines*. arXiv: 0709.3967v1, Cornell University Library.

Gleeson, E., McGrath, R. and Treanor, M. (Eds). 2013. *Ireland's Climate: the Road Ahead*. Dublin: Met Éireann. ISBN 978-0-9521232-6-2. p 101.

Haarsma, R. J., Hazeleger, W., Severijns, C., de Vries, H., Sterl, A., Bintanja, B., van Oldenborgh, B. J. and van den Brink, H.W. 2013. More hurricanes to hit western Europe due to global warming. *Geophysical Research Letters* 40: 1783–1788.

Hastie, T., Tibshirani, R. and Friedman, R. 2001. *The Elements of Statistical Learning – Data Mining, Inference and Prediction*. Springer.

Haralick, R., Shanmugam, K. and Dinstein, I. 1973. Textural features for image classification. *IEEE Transactions on Systems, Man and Cybernetics* 3: 610–622.

Honkavaara, E., Litkey, P., Nurminen, K. 2013. Automatic Storm Damage Detection in Forests Using High-Altitude Photogrammetric Imagery. *Remote Sensing* 5: 1405–1424.

Jackson, R.G., Foody, G.M. and Quine, C.P. 2000. Characterising windthrow gaps from fine spatial resolution remotely sensed data. *Forest Ecology and Management* 135: 252–260.

Jonikavičius, D., Mozgeris, G. 2013. Rapid assessment of wind storm-caused forest damage using satellite images and stand-wise forest inventory data. *iForest* 6: 150-155.

Kempeneers, P., Sedano, F., Strobl, P., McInerney, D. and San-Miguel, J. 2012. Increasing Robustness of Postclassification Change Detection Using Time Series of Land Cover Maps. *IEEE Transactions on Geoscience and Remote Sensing* 50: 3327–3339.

McGrath, R. 2015. *Impact of Storm Darwin on Ireland: Description of the Event and Assessment of Weather Forecasts*. Met Éireann Technical Note 64.

McInerney, D. and Kempeneers, P. 2014. *Open-source Geospatial Tools: Applications in Earth Observation*. Springer. Pp. 358 ISBN-10: 331901823X.

Mitchell, S.J. 2013. Wind as a natural disturbance agent in forests: a synthesis. *Forestry* 86: 147–157.

Nelson, M.D., Healy, S.P, Moser, K.W. and Hansen, M.P. 2009. Combining satellite imagery with forest inventory data to assess damage severity following a major blowdown event in northern Minnesota, USA. *International Journal of Remote Sensing* 30: 5089–5108.

Ní Dhubháin, Á. 1998. The influence of wind on forestry in Ireland. *Irish Forestry* 55: 105–113.

O'Connor, B., Dwyer, N. and Cawkwell, F. 2008. Satellite remote sensing as a tool for monitoring vegetation seasonality. *Proceedings of the Remote Sensing and Photogrammetry Society Conference 2008*. "Measuring change in the Earth system". University of Exeter, 15th–17th September 2008. pp 1–4.

Olthof, I., King, D.J. and Lautenschlager, R.A. 2004. Mapping deciduous forest ice storm damage using Landsat and environmental data. *Remote Sensing of Environment* 89: 484–496.

Sedano, F., Kempeneers, P., Strobl, P., McInerney, D. and San-Miguel, J. 2012. Increasing spatial detail of burned scar maps using IRS-AWiFS data for Mediterranean Europe. *Remote Sensing* 4: 726–744.

Serbin, G. and Green, S. 2015. *Optical Remote Sensing of Permanent Deforestation in Ireland*. 9th Irish Earth Observation Symposium. Irish Earth Observation Symposium. National University of Ireland. Galway. 21st–22nd October 2015.