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1 Article

## 2 Detection of Old Diffusive Windthrow Using Low 3 Cost Resources. the Case of Xynthia Storm in the 4 Vosges Mountains, 28 February 2010

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12 **Abstract:** Unlike the contiguous windthrows, the diffuse windthrows occurred as a result of wind  
13 gusts of lower speed (100-140 km/h) than in the first case (>140 km/h) are much more difficult to  
14 detect due to their much lower areas and due to their very large number, of several hundreds in the  
15 wooded mountain massifs. The objective of this research is to present a rapid procedure for the  
16 detection of the diffuse windthrows based on low cost, Landsat type images, knowing that certain  
17 sensors cannot be accessed without significant investments. Our application is based on the study  
18 of effects caused by the Xynthia storm in the Vosges Mountains in the North-East of France, on 28  
19 February 2010. Thus, based on two sets of Landsat satellite images, we used the “dark object”  
20 approach and the Disturbance Index, as well as a classification of the images before and after the  
21 storm, resulting in a change map. Following the detection process, 257 scattered polygons were  
22 detected, totalling 229 ha. For validation purposes, high-resolution images and orthophotoplans  
23 taken before and after storm were used. The error matrix was calculated, achieving an overall  
24 accuracy of 86%, which confirms the quality of our analysis and supports this procedure for  
25 detecting diffuse windthrow based on low cost resources.

26 **Keywords:** windthrow; Xynthia storm; Landsat imagery; limited data.

27

### 28 1. Introduction

29 Storms are known to be the most destructive natural disasters for forests in terms of frequency  
30 of occurrence, damages caused and their spatial extent [1,2,3]. Such a meteorological phenomenon  
31 occurring in France was the Xynthia storm, on 28 February 2010. Although it did not have the  
32 exceptional nature of the catastrophic Lothar storm in 1999 [4,5] or Klaus storm in 2009 [6] by its  
33 maximum speed (160 km/h), it caused major damages, i.e. thousands of cubic meters of forest  
34 destroyed in Lorraine and Alsace. The Pôle interrégional de la Santé des Forêts du Nord-Est Institute  
35 [7,8] mentions for the Lorraine region some 15,000 m<sup>3</sup> of destabilized spruce at Louppy-sur-Loison  
36 (department of Meuse), some pine forests in the Wardnt Plateau (department of Moselle), and, to a  
37 lesser extent, some aged beech forests. In the Alsace region, the same source mentions some limited  
38 destabilization in forest border areas or in areas where there is no longer any interest in logging.  
39 Besides the official reports [9,10,11,12] the press of the time, i.e. The Vosges Martin newspaper,  
40 LOR'Actu, France Culture, but also other local and regional media sources have presented more  
41 dramatically the effects of this storm on the forests of Vosges, suggesting that many more points  
42 would have been affected, as the windthrow had a diffuse character [13,14]. Even if several years

43 have passed since that event, through remote sensing images that stored the condition of vegetation,  
44 in this paper we will try to identify the affected points that seem to be masked by the extent of the  
45 forest crop.

46 The detection of the changes caused by storms, be they contiguous or diffused, is very important  
47 in order to establish spatial and temporal trends in the rehabilitation and management of forest  
48 resources. Papaik and Canham [15] show that storms can be seen as an integral part of the forest  
49 ecosystems functioning, but that the detection of changes must be conducted in order to know and  
50 manage ecosystems and forest resources. The use of remote sensing in forestry applications is today  
51 an extremely useful tool to acquire knowledge and conduct the management of forest ecosystems.  
52 The information provided by this tool on the interaction between the atmosphere and the forest for  
53 the purpose, for example, of locating the damages caused by storms in the context of climate change  
54 [16,17,18,19] or for carbon sequestration potential [20,21] is a must because it can help extrapolate this  
55 information to larger spatial scales.

56 Huang et al. [22], proposed a method for the detection of forest areas affected by storms, the use  
57 of vegetation indices and the Tasselled Cap Transformation. Based on this transformation, Healey et  
58 al. [23] developed the Disturbance Index, used for windthrow detection. The idea behind the index  
59 is that disturbance sites exhibit higher brightness, and lower greenness and wetness values compared  
60 to the undisturbed forests [24]. This procedure was then optimized and adapted to the purpose of  
61 continual monitoring of forest disturbances through time series images [25,26,27,28].

62 Another direction for the development of remote sensing to identify windthrows refers to semi-  
63 automatic or automatic procedures. Stach et al. [29] proposed mapping by optical and radar remote  
64 sensing. Huang et al. [30] developed dark object concept and support vector machines to automate  
65 forest cover change analysis, while Kennedy et al. [31] used LandTrendr segmentation algorithms in  
66 order to develop maps of forest disturbance and regrowth.

67 Regarding the methodology applied to assess the consequences of Martin and Lothar hurricanes  
68 in 1999 on the forests of France, Stach et al. [32] concluded that the best results were those achieved  
69 by radar remote sensing.

70 Due to the meteorological risk events causing significant damages throughout recent decades,  
71 France, but also other countries in Western Europe experienced large windthrow areas. Therefore,  
72 the researchers from the French National Forest Inventory [6,33] have developed a new semi-  
73 automatic methodology, the "7 point method" to map the felling damages caused by the storms and  
74 to monitor the land use adapted to varied landform conditions. The principle of the method is based  
75 on the "pixel per pixel" comparison of two satellite images recorded before and after the storm. The  
76 "pixel per pixel" and "spectral band with spectral band" difference is performed to highlight the  
77 radiometric evolution between the images before and after the storm. In order to detect the  
78 windthrows, the "7-point method" combines the change detection techniques with an automatic  
79 image segmentation phase, namely the delimitation of homogeneous areas in terms of radiometry  
80 and texture. The detected forest changes caused by the storm are highlighted, the damages identified  
81 in each plot are classified and, in the end, the damage map for the analysed area is obtained by  
82 combining all the previous results. This methodology has been used to map the windthrows and  
83 damages caused by the Lothar and Martin storms in 1999 in Forêt des Landes, South-Western France.  
84 The windthrow mapping in the Vosges department in the year 2002 was carried out by combining  
85 remote sensing for the plain and hill areas with aerial photogrammetry for the mountain [33]. The  
86 forest damages caused by the Klaus storm occurring in January 2009 were also evaluated using the  
87 7-point method [6]. The working principle of these methods is the achievement of real-time  
88 information by transforming the remote sensing images into vegetation state indices needed to  
89 identify the disturbances or abnormalities occurring in the forest areas [34].

90 The wider and wider use of very high-resolution (VHR) remotely sensed images has stimulated  
91 the development of object-based methods and data mining techniques, which were much more  
92 effective for change detection [35]. Bauman et al. [24] have developed a methodology for detecting  
93 and analysing windthrows for various meteorological phenomena. Moreover, they have managed to  
94 separate the disturbances due to the storms as compared to those caused by massive forest cuttings

95 in the forest areas, as well as to the other land cover classes. This study was implemented in a  
96 temperate zone in Russia and in an area in the USA boreal forests. The methodology applied in this  
97 study was based on the detection of windthrows using the Disturbance Index that was designed  
98 considering the Tasselled Cap transformation and the “dark object” approach.

99 The purpose of our application is to detect the forest areas in the Vosges Mountains affected by  
100 the Xynthia storm in February 2010, as it is well known that there are diffuse windthrows, without  
101 taking into account more sophisticated but also more expensive imaging resources, such as those  
102 mentioned above, but, on the contrary, using Landsat's least expensive satellite imagery.

## 103 2. The study area and the storm event

104 The study area is represented by the Vosges Mountains (7,360 km<sup>2</sup>, of which 4,400 km<sup>2</sup> are forest  
105 area), located in the North-Eastern part of France (Figure 1), in low altitude mountains, with 14 peaks  
106 exceeding 1,000 m and the maximum altitude, of 1,424 m, in the Grand Ballon Peak. The mountains  
107 expand longitudinally over approximately 200 km until the German border, along the west bank of  
108 the Rhine River. Their maximum width is 60 km in the South, 20 km in the North and only 4 km in  
109 their upper third part. The Southern part of the massif consists in crystalline schists, while the  
110 Northern part is composed largely of sandstones. The lithology of the area has been heavily  
111 influenced by glacial erosion, with many glacial lakes being found here.

112 Due to the geographic location, the Vosges Mountains experience two climate influences:  
113 oceanic and semi-continental. West from the Vosges Mountains, the relief has lower altitudes  
114 (Parisian Basin and Lorraine Plateau). Therefore, the air masses propelled by the oceanic disturbances  
115 are forced to escalate the Western flanks of the Vosges Mountains generating severe weather  
116 conditions and strong wind gusts. However, the storms in the Vosges are not as severe or devastating  
117 as those on the Atlantic coast, although they are reactivated by the escalation of the mountains. This  
118 is because they weaken in intensity due to the distance of about 1,000 km that these storms have to  
119 pass through until the North-East of France, in the exit area from the French territory. The dominant  
120 winds are in the Western sector, and in case of storms such as Lothar on 26 December 1999 and  
121 Xynthia on 28 February 2010, blow in gusts exceeding 170 km/h on the mountains peaks. This was  
122 also the case of some tornadoes, such as the one on 11 July 1984, when some extremely strong gusts  
123 were recorded, of 200 km/h.

124 The massif is predominantly covered by forest (60% of the surface of the mountains today),  
125 especially conifers (pine and spruce), which is up to the altitude of 800-1000 m, while towards the  
126 foothills of the mountains there is a transition to deciduous forests, as well as to open meadows that  
127 were created by man for agricultural practices. The forest cover of the Vosges Mountains ranks  
128 second in France in terms of extent, after the Landes forest. It covers the East of Lorraine, the Alsace  
129 mountain region and the North-East of the Franche Comté region. The Vosges forest is the first region  
130 of France in terms of pine, fir and spruce production, with a crop of 1.5 million m<sup>3</sup> of logs, namely 1/3  
131 of the country's total production. Without the human intervention, with the most intense  
132 deforestations in the 18<sup>th</sup> and 19<sup>th</sup> centuries, the forest would have covered the entire mountain area,  
133 except the highest peaks and areas exposed to the weather. Nowadays, the authorities apply the  
134 sustainable management principle, so that despite the significant harvest, the forest of Vosges is  
135 progressing, the annual harvest being much lower than the growth rate [6].

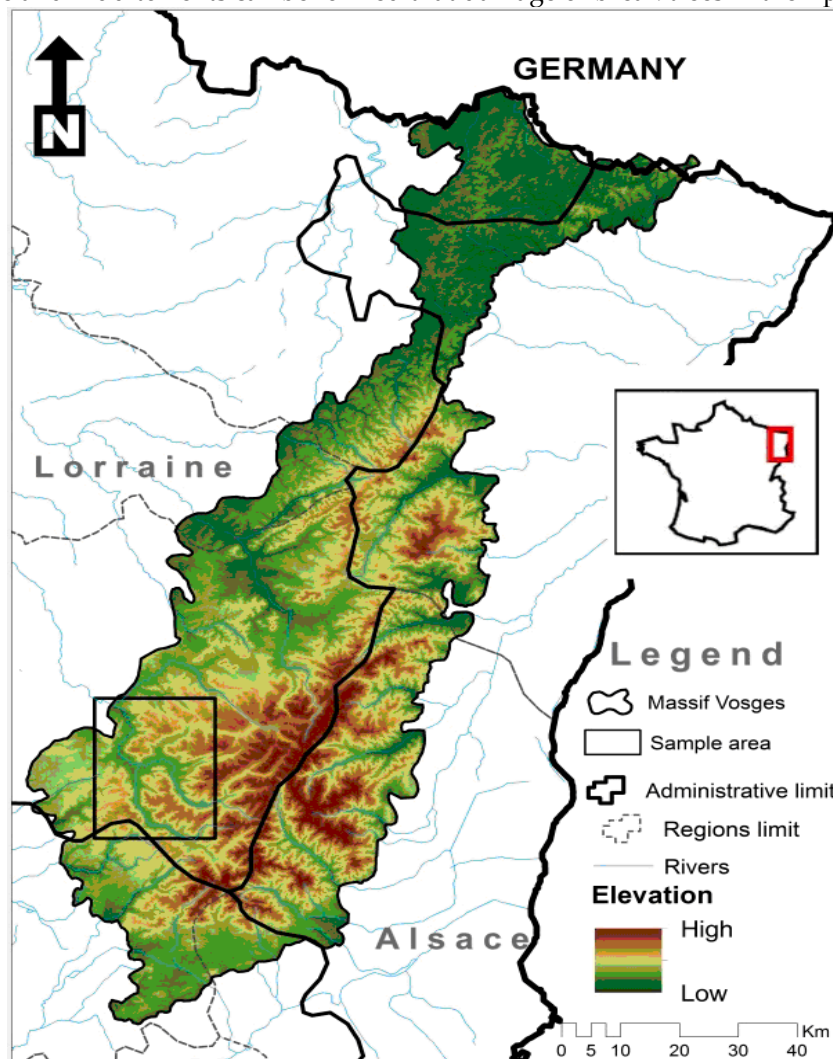
136 It is worth mentioning that the Vosges Mountains host 2 regional natural parks (Parc Naturel  
137 Régional des Vosges du Nord, Parc Naturel Régional des Ballons des Vosges), Réserve de biosphère  
138 transfrontalière des Vosges du Nord-Pfälzerwald (France-Germany), as well as some national natural  
139 reserves related to the presence of the forest.

140 But sometimes weather conditions are so severe that trees are broken or uprooted. The most  
141 frequent and extensive windthrows in the Vosges Mountains were caused by wind gusts either due  
142 to tornadoes formed during some hot summers or due to winter storms.

143 The tornadoes monitoring and research group Keraunos, Météo France, as well as the historical  
144 contributions of the CLI.M.A.57-67-68 association and the works of Garnier [37] and [38], enable us

145 to list the most devastating tornadoes mentioned for the Vosges: 13.08.1770 at Gérardmer, 29.05.1807  
 146 at Lusse, 11.06.1880 at Eloyes, 10.07.1968 a tornado in the Eastern part of Lorraine, 30.06.2012 at  
 147 Gérardmer and 13.05.2015 at Gerbépal. It is worth mentioning that most often such tornadoes or mini-  
 148 tornadoes are produced in the Western part of the Vosges Mountains. In remote sensing studies  
 149 careful consideration should be given when selecting images for the consequences of certain episodes  
 150 with wind gusts in order to avoid confusion and to correctly identify the cause of windthrows, be  
 151 they summer tornadoes or winter storms.

152 A very violent convective phenomenon similar to a mini-tornado called "derecho" occurred on  
 153 16 September 2015 in the Centre and East of France, which affected also the Western part of the  
 154 Vosges Mountains and caused significant windthrows. Even in the winters with remarkable  
 155 snowfalls (1969/1970, 1994/1995, 2005/2006) some trees were damaged or blown over by "heavy  
 156 snow", sometimes in combination with a stronger wind. Rarely, in the case of sudden snow removal,  
 157 stone and mud torrents can be formed that damage or break trees in their path.



158

159 **Figure 1.** Location of Vosges Mountains and a sample area highlighted later.

160 Due to location, climatic conditions and topography, the Vosges Mountains area has often been  
 161 affected by major winter storms that have led to windthrows on extensive forest areas, causing the  
 162 greatest damages if we also relate to other damaging causes for forests. Meteo France distinguishes  
 163 12 types of storms, [39] with the most frequent being the North and West oceanic storms. Hence, the  
 164 Vosges Mountains area, especially the Northern part, is on the storm's travel path. Obviously, the  
 165 French coastline is the most exposed and feels the maximum strength of any storm originating in the  
 166 Atlantic. Then, the storm's strength gradually weakens towards the interior of the country. This

167 explains why windthrows in the North-Eastern France and the ones from the Vosges Mountains have  
168 a local character or are often diffuse.

169 The Xynthia winter storm occurred from a low pressure system formed in the subtropical area  
170 south of the Azores on 25 February 2010. The southern flow of cold air masses from the altitude  
171 caused the formation of a depression over the Centre and Eastern part of the North Atlantic Ocean.  
172 The high temperature difference between the extremely hot air flow above the Africa and the cold air  
173 in the Eastern Atlantic Ocean has accentuated the decrease in atmospheric pressure that led to the  
174 formation of the powerful Xynthia cyclone. The cyclone experienced a rapid intensification affecting  
175 8 countries, and causing 65 deaths [40] in its movement from SW to NE (Figure 2). The depression  
176 core reached the Gascogne Bay on the evening of 27 February bringing violent winds from the  
177 Southern sector that blew in the Pyrenees Mountains at 242 km/h. On the morning of 28 February,  
178 Xynthia furiously hit the French coastline, the pressure at the centre of the cyclone dropped to 968  
179 hPa and the wind gusts reached 120-160 km/h. Following its path, Xynthia crossed the South-West  
180 and Central France, approaching the Vosges Mountains from the South-West direction on 28  
181 February 2010. Wind gusts of 172 km/h were recorded in the Markstein Resort (68) located at 1184 m  
182 altitude, but also the other mountain or resorts in the neighbourhood of the Vosges Mountains  
183 recorded notable wind gusts: Septsarges (55) 147 km/h, Goin (57) 136 km/h, Metz (57) 136 km/h,  
184 Belmont (67) 134 km/h, and Vagney (88) 133 km/h. According to the classification cited above,  
185 Xynthia was of the SW type, with an extremely southern origin (close to the Tropic of Cancer) for a  
186 typical winter storm. It had an atypical trajectory and its effect was felt in North-Eastern France  
187 exceeding its borders, until the Baltic Sea, which showed that winter storms could threaten the entire  
188 country. From a statistical point of view, Bedach and Hofherr [40] estimate that storms as severe as  
189 Xynthia have an average occurrence frequency in France once every two years.

190 The existing literature [4,37,38,39,41,42] allowed us to locate Xynthia in a series of devastating  
191 storms that have hit the Vosges Mountains (Table 1).

192 **Table 1.** The main recorded winter storms that caused windthrows in the Vosges Mountains

Date	Affected area	Notable characteristics
1698	N-E of France	
1716	N-E of France	
1739, 14-18.01	N-E of France	Major forest damage in the Vosges Mountains
1836, 23.03	All France	
1866, 10-11.01	1866, 10-11.01	
1879, 20.02	All France	130 km/h gusts, Meurthe-et-Moselle very affected
1882, 26-27.03	All France	
1886, 27.02	N-E France	
1892, 29-30.03	Alsace	0,5 M m <sup>3</sup> felled trees
1896, 04.12	N-E France	
1900, 13.02	Lorraine	
1902, 31.01-01.02	Vosges	2,2 M m <sup>3</sup> felled trees
1920, 10-14.01	Moselle, Alsace	1,0 M m <sup>3</sup> felled trees
1924, 08.10	N-E France	
1935, 22-23.02	N-E France	
1940, 14.03	Lorraine	180 km/h wind gusts in Nancy
1952, 12-13.12	Lorraine, Alsace	112 km/h wind gusts in Metz-Frescaty, major windthrows
1958, 02	Vosges	1.2 M m <sup>3</sup> felled trees
1962, 16.02	Lorraine, Alsace	151 km/h wind gusts at Metz
1967, 02	N-E of France	130 km/h wind gusts at Bale-Moulhouse; 3.6 M m <sup>3</sup> felled trees
1990, 25.01	N-E of France	DARIA storm, 137 km/h wind gusts at Nancy-Ochey
1990, 03.02	Almost all France	HERTA storm

1990, 26-28.02	Almost all France	VIVIANE storm
1990, 03	Lorraine, Alsace	WIEBKE storm, 144 km/h wind gusts at Metz
1994, 28.01	Landes, Alsace	1.2 M m <sup>3</sup> felled trees
1999, 26-28.12	All France	LOTHAR storm, 155 km/h wind gusts at Nancy, 140 M m <sup>3</sup> felled trees from which Lorraine 29.5 and Alsace 6.5
2006, 03.10	Alsace	RENATE storm, 149 km/h wind gusts at Markstein
2006, 08.12	Alsace	VERA storm, 136 km/h wind gusts at Markstein
2009, 9-10.02	Alsace	QUINTEN storm, 166 km/h wind gusts at Markstein
2010, 28.02	Almost all France	XYNTHIA storm
2011, 15-18.12	N of France	JOACHIM storm, 192 km/h wind gusts at Markstein, limited windthrows, dispersed in the coniferous massifs
2013, 27-28.10	N-E of France	CHRISTIAN storm, 162 km/h wind gusts at Markstein
2014, 13.02	N-E of France	TINI II storm, 151 km/h wind gusts at Markstein, 17,000 m <sup>3</sup> diffuse windthrows

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As Bock et al. [43] stated, the institutes in France involved in the management of the forest resources - ONF (Office National des Forêts), IDF (Institut pour le Développement Forestier) and the INRA (Institut National pour la Recherche Agronomique), have studied the dependence between windthrows and wind speed. In regular beech forests, isolated windthrows occur at a wind speed ranging between 100 and 120 km/h, multiple diffuse windthrows occur at a 120-140 km/h wind speed, and large scale and frequent windthrows occur at speeds over 140 km/h. The same authors also found that at the height of the trees below 23-24 m the windthrows were rarer, but at wind speeds over 120 km/h the frequency of windthrows increased proportionally to the height of trees.

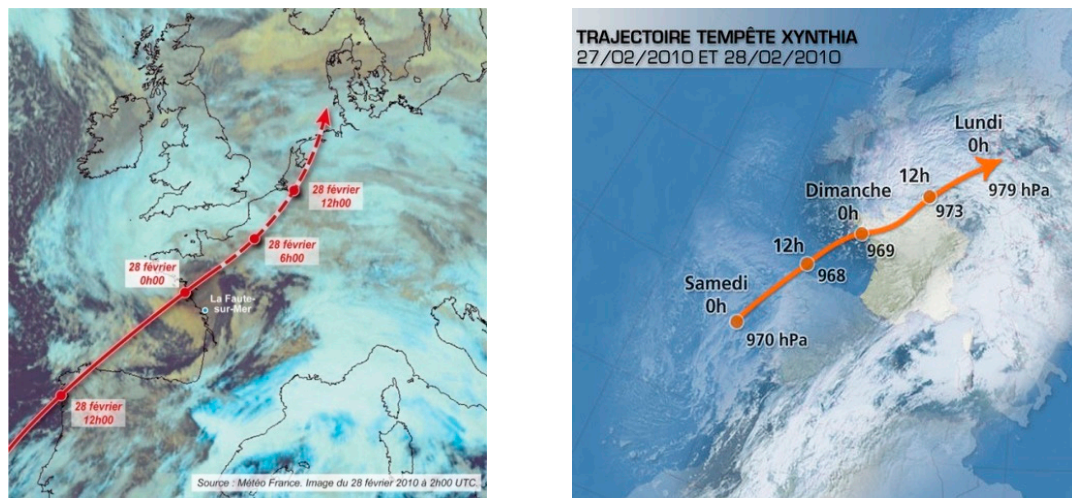


Figure. 2. The trajectory of the Xythhia storm, (source [39])

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### 3. The alternative of using low cost resources

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Nowadays, in the context of the impetuous development of remote sensing techniques, there is a natural preference for high and very-high-resolution (VHR) remote sensing images. Unfortunately, these are expensive and more difficult to access. We also have to admit that sometimes it is not possible to capture real-time images or create time series of images. Maybe this would be possible, but the cost of raw data purchases is too high. Therefore, we would like to assess if less expensive and easier-to-acquire images, such as Landsat, despite their lower resolution, would still be sufficient and capable of detecting diffuse windthrows. Starting with 2014 Sentinel Radar images are also free, but obviously these cannot be considered because the event we studied occurred in 2010. One should mention that in the case of the free images, very expensive software is often needed to process them.

213 But if the purpose of a research is to rebuild the old windthrow trees, obviously, only the sources  
214 produced by the older satellites or having an archive (Landsat from 1980) can be accessed.

215 The availability of satellite data varies and choosing the best sensor is very important in order  
216 to select the data which better suit our purpose and to get more accurate results. When detecting  
217 windthrows using optical satellite imagery it is important to know which sensor is appropriate.  
218 Schwarz et al. [44] summarized the criteria to be considered in choosing the appropriate sensor,  
219 namely: *data availability, spectral resolution, spatial resolution* and *temporal resolution* (to increase the  
220 probability of achieving useful cloud-free data). Besides availability and resolution, the cost of data  
221 represents also an important factor to be considered. Satellite imagery products vary in their spatial  
222 and spectral resolution, geographic and temporal coverage, cloud cover, security regulations, and  
223 price [45]. The most frequently used and inexpensive data sources for detecting windthrows are the  
224 remote sensing images offered by the Landsat sensor [48]. These are basic sources due to the free of  
225 charge images and to the spatial, spectral and temporal details they provide for the mapping of the  
226 area damaged by storms.

227 The free of charge availability of Landsat archive and the large geographic coverage provide the  
228 opportunities to conduct studies over a long period of time and over a large area [47-49]. Beside the  
229 medium resolution provided, Landsat images at a spatial resolution of 30 m were successfully used  
230 to detect windthrows in various areas [23,24,27,50-53]. However, the increasing availability of high-  
231 resolution satellite imagery offers the potential to acquire data with fine spatial resolution (e.g.  
232 WorldView, Ikonos, Quickbird), but the cost of these data is a hindering factor in using them. Jackson  
233 et al. [54] showed that high-resolution imagery, like LIDAR, offered a great potential to detect  
234 windthrows, but they required more basic operating instructions.

235 In this study we chose to use Landsat data to detect the windthrows along the Vosges  
236 Mountains. The first reason in choosing Landsat sensor was the wide swath and the low cost. The  
237 medium resolution Landsat data is not as sharp as high-resolution images, but the amount of  
238 information it contains along with the large area coverage make this data suitable for large- or small-  
239 scale studies. We studied the diffuse windthrows and the exact location of these disturbances was  
240 unknown. Therefore, the availability and the coverage represented another factor in choosing the  
241 sensor. The Landsat TM and ETM+ program covers the entire world within 16 days and the images  
242 are saved in an archive, so the possibility to find cloud-free images is increasing due to this  
243 availability of free data [44]. Each type of satellite images has advantages and disadvantages in  
244 detecting windthrows. Malthus et al. [55] have developed a comparative study to emphasize the  
245 advantages, limitations and even prices, where possible, of current remote sensing image sources  
246 used in *commercial forestry*. Similar comparisons have been developed by Suarez et al. [56], which  
247 compared optical techniques with RADAR and LIDAR sensors. Melesse et al. [57] presented the  
248 characteristics of 20 different satellite sensors, while [3] summarised the specification of sensors used  
249 for *forest disturbance detection*.

250 The table below (Table 2) summarizes the characteristics of the most important satellite data  
251 used in windthrow detection and forest cover monitoring. The most important differences between  
252 these data are the spatial resolutions, e.g. from 30 m for Landsat-7 multispectral data to 1 m and even  
253 under 1 m for the Ikonos, WorldView, and QuickBird data. But when detecting and assessing  
254 windthrows, the choice of the appropriate sensor will depend on the availability of data, cost, scale  
255 of the fragmented landscape and area of interest, because the high resolution imagery is not available  
256 globally, like Landsat data. If the exact small scale (< 0.5 ha) delineation of the windthrow is needed,  
257 then the high-resolution imagery is suitable. But if the goal is to detect large scale windthrows  
258 quickly, then the medium resolution data is more useful [44].

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**Table 2.** Characteristics of a number of remote sensing sensors

Sensor	Years	Number of Bands	Multispectral resolution (m)	Panchrom. resolution (m)	Repeat cycle	Scene size (km)	Cost per sq. km
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Landsat 4-5 MSS	1982 1999	4	80	—	18days	185 x 185	Free
Landsat 4- 5 TM	1982 2012	7	30 120 - thermal	—	16 days	185 x 172	Free
Landsat 7 ETM+	1999	8	30 60 - thermal	15	16 days	185 x 172	Free
Landsat 8	2013	11	30	15	16 days	185 x 180	Free
ASTER	1999	14	15 – band 1-3 30 – band 4-9 90–band10-14	—	1- 2 days	60	Free (on- deman d)
MODIS Terra	1999	36	250 - 2 bands	—	1-16 days	2330	Free
MODIS Aqua	2002		500 - 5 bands 1000-29bands				
SPOT 1-3	1986 1997	3	20	10	26 days	60 x 60	\$1,200 per scene
SPOT 4	1998 2013	4	20	10	26 days	60 x 60	\$1,200 per scene
SPOT 5	2002	4	10	2.5 / 5	26 days	60 x 60	\$2,700 per scene
SPOT 6-7	2012	4	6	1.5	26 days	60 x 60	\$5.15
IKONOS	1999	4	4	1	14 days Less than 3 days	11.3	\$30- 53 per scene
QuickBird	2001	4	2.4	0.61	Between 1 and 2.8 days	16.8	\$18
FORMOSAT 2	2004	5	8	2	daily	24x24	
Pléiades 1A-1B	2011	4	2	0.5	26 days daily	20	\$13 - 40
WorldView-1	2007	1	—	0.46	3.7 days ( for 0.52 m) 1.1 days (for 1 m)	17.6 x 14	\$14 - 48
WorldView-2	2009	8	1.84	0.46	Up to 1.1 days	16.4	\$14 - 58
WorldView-3	2014	28	1.24	0.31	between 1 to 4.5 days	13.1	\$19
WorldView-4	2016	4	1.24	0.31	less than 3 days	—	—
RapidEye	2008	5	5		between 1 to 5.5 days	25x25	\$14 - 55
Sentinel 1A and 1B	2014, 2016	1 SAR band	variable		5 to 12 days	—	free
Sentinel 2A and 2B	2015, 2017	13	variable		5 to 10 days	—	free

\* Source [60,61]

260

261

262

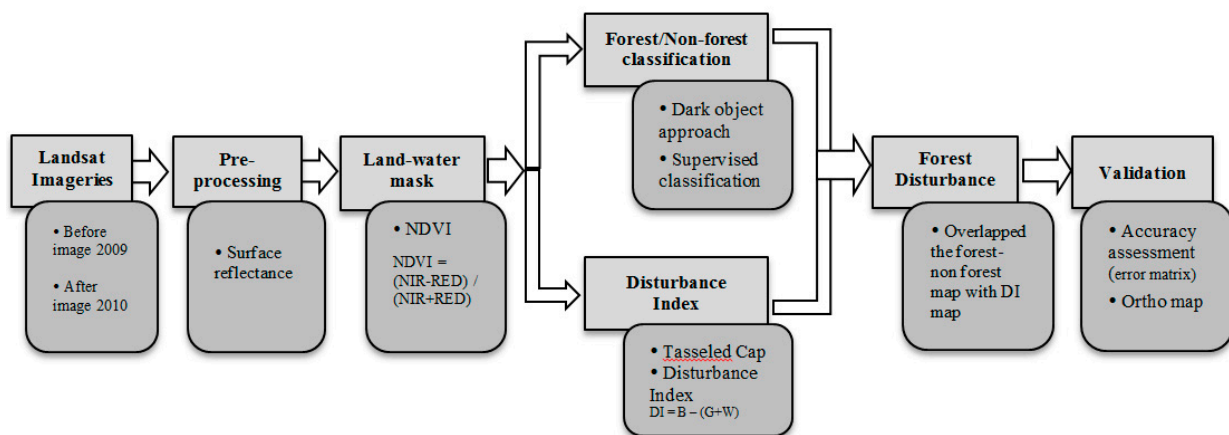
263

\*\* Prices are only estimates based on online sources, and may vary and the price can increase due to the demanding rules set by the providers. E.g. - usually the minimum order area for archive imagery is 25 sq. /km with a 2 km (digital globe) or 3 km (GeoEye) minimum order width.

264 The free access policy for Landsat data has made this data more and more frequently used in  
 265 remote sensing studies [60,61]. However, with the accessibility of these data, there is a challenge to  
 266 find images without clouds or with very little cloud coverage in the analysed area, because clouds  
 267 can significantly influence the reflection from different spectral bands [62]. This is an issue we have  
 268 also faced and we will present next how we have solved this shortcoming

#### 269 4. Materials and Methods

270 In this study we aimed to highlight the applicability and efficiency of Landsat data in detecting  
 271 diffuse windthrows caused by the Xynthia storm that crossed the Vosges Mountains on 28 February  
 272 2010. Windthrow detection depends on the affected area. If the affected area is larger, the detection  
 273 capability increases, together with the results accuracy of the Landsat satellite images based analysis.  
 274 Figure 3 illustrates the methodological workflow.



275

276

Figure 3. Methodological steps

277 We started with the pre-processing of satellite imagery, namely converting them from digital  
 278 numbers into reflectance. The next step consists in masking the water bodies and dark soil to avoid  
 279 these pixels being confused with pixels corresponding to the vegetation areas, by using the NDVI  
 280 index values. Then the images were classified into forest and non-forest areas. The classification was  
 281 made for the two images, before and after the storm, respectively. Then the difference between the  
 282 classified images was made, resulting into the identification of areas with lost forest vegetation.

283 In addition, to improve the result obtained in the previous step, the Disturbance Index (DI) was  
 284 used. The calculation of DI is made based on the Tasseled Cap bands. After overlapping the two  
 285 resulting images we obtained the forest changes map. Then, the validation of results was carried out.  
 286 The evaluation of results depends on the data and information used. The accuracy can be directly  
 287 influenced by the quality and availability of the ground data (the resolution of orthophotos, high-  
 288 resolution satellite imagery). The first step in results validation is to calculate the accuracy assessment  
 289 and the Kappa statistic. Another validation was made by overlapping the polygons resulting from  
 290 the change map with the orthophotos from 2009 and with the RapidEye satellite image from 2010.

##### 291 4.1. Pre-processing, land-water and cloud mask

292 Landsat satellite images were used for windthrow detection. The images were purchased for the  
 293 previous year and the year after the meteorological phenomenon (28 February 2010) that has led to  
 294 the fall of trees in the Vosges Mountains. Thereby, a multi-temporal set of Landsat 5 TM images (with  
 295 7 spectral bands - 30 m spatial resolution) was used. The images were acquired on different days  
 296 17.06.2009, before the Xynthia storm, and on 4.06.2010, after the phenomenon. The Landsat images  
 297 were downloaded freely from the [63] website. Table 3 shows that between the two dates of image  
 298 selection there were no meteorological events with extreme wind gusts, no storms or tornadoes.  
 299 Therefore, the data reflected by the two images cannot be artefacts. We selected no clouds or very

300 few clouds images that were recorded during the growing season and these were purchased for the  
301 same vegetation season (June), to reduce the impact of vegetation in different seasons.

302 **Table 3.** The characteristics of the images that were used for the Vosges Mountains area

Date of the Xynthia storm	Path/Row	Lat/Long	Previous to Xynthia	After Xynthia
27-28.02.2010	196/026-027	48.9/6.9	17.06.2009	4.06.2010

303  
304 In order to use the satellite images to detect changes occurring at the ground surface, several  
305 steps are required, namely: selecting the images that best fit the intended purpose, orthorectification,  
306 georeferencing, various corrections, calculating some indices to enhance the data information [64].  
307 The Landsat satellite images provided by USGS have already been radiometrically and geometrically  
308 corrected, but for the proposed operations we needed the values of the reflective satellite images.  
309 This operation was done using the formulas given by Chander & Markham [65]. The first step was  
310 to pre-process the two sets of images, before and after the storm, by converting the digital numbers  
311 into spectral radiance using the equation:

$$312 \quad L_{\lambda} = (\text{gain} * \text{DN}) + \text{bias}_{\lambda} \quad (1)$$

314 Where:

315  $L_{\lambda}$  - the spectral radiance at the sensor level and referring to the wavelength  $\lambda$  for the specific band;

316  $DN$  - Digital Number;

317  $gain$  and  $bias$  - are specific calibration parameters determined before launch.

318

319 For the relatively clear Landsat images, a reduction in variability of images can be made by  
320 converting spectral radiance, calculated using equation (1), into surface reflectance or albedo. To  
321 obtain surface reflectance, the fraction of solar energy reflected on a certain wavelength, the following  
322 equation was used:

$$323 \quad R_{\lambda} = (\pi * L_{\lambda} * d^2) / (ESUN_{\lambda} * \sin\theta_s) \quad (2)$$

324 Where:

325  $R_{\lambda}$  - Spectral radiance at the sensor's aperture;

326  $L_{\lambda}$  - Spectral radiance at the sensor's aperture calculated through equation 1;

327  $d$  - Earth-Sun distance [astronomical units];

328  $ESUN_{\lambda}$  - Mean exoatmospheric solar irradiance [66];

329  $\sin\theta_s$  - solar zenith angle in degrees

330

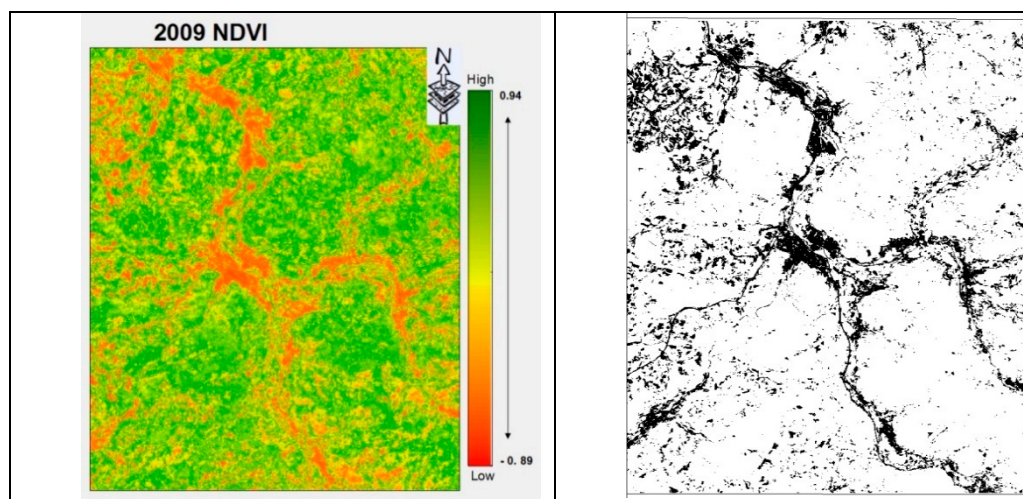
331 The next step consists in masking the clouds, as we mentioned previously. This step is essential  
332 because during the detection process, the pixels corresponding to the clouds or their shadows can be  
333 confused with darker vegetation pixels, such as the coniferous forests. Clouds are difficult to detect  
334 on Landsat images, due to the spectral properties of these images and the complexity of the clouds  
335 [67]. It may be more difficult to distinguish the shadow of clouds from "false shades" [64] given by  
336 the dark soils, the topographic shadows, water, etc. For example, Huang et al. [26] reported  
337 difficulties in separating shadows from the spectral response of waters (cited by [62]). On the other  
338 hand, the lack of adequate images may introduce errors in the process of masking the clouds and  
339 lead to the inability to differentiate between the cloud shadows and the topographic shadows where  
340 there are areas with shadow potential [61,68]. If the areas with changes are relatively small, this error  
341 time significantly decreases the detection accuracy of the changes [67]. The clouds and associated  
342 shadows were separated through a classification of associated pixels and excluded from the  
343 subsequent analyses of the changes occurred in the studied area. After applying this mask, the areas  
344 where clouds and shadows were located received the value "No data", not taking into account  
345 subsequent processing.

346 In addition to the masking of clouds and their associated shadows, it is necessary to apply  
 347 another mask for some non-forest dark surfaces such as water, dark soil, and dark impervious  
 348 surfaces because these can be as dark as or even darker than forest pixels [26]. To identify and remove  
 349 these pixels we used the method proposed by Huang et al. [26], which is based on the spectral  
 350 properties of water bodies and dark soil. Pixels are classified as water or dark soil if they have reduced  
 351 reflection in the SWIR band and if they have low NDVI index values calculated based on the RED  
 352 and NIR reflectance bands:

$$353 \text{NDVI} = (\text{NIR} - \text{RED}) / (\text{NIR} + \text{RED}) \quad (3)$$

356 After calculating the Normalized Vegetation Difference Index, a threshold was set to delineate  
 357 the land-cover classes from the masked areas covered by water and soil, respectively. In this study  
 358 the threshold 0.25 was used. To exemplify the result we performed a zoom on a 26.6 km x 20.5 km  
 359 sample area, i.e. on a 54,613 ha area, which has the Remiremont city in the centre (Figure 4), a sample  
 360 that was also used for the other examples. This step made it possible to identify and eliminate pixels  
 361 that may be problematic throughout the next steps.

362  
 363



364 **Figure 4.** NDVI values (a) and masking of non-vegetated dark objects (b)

#### 365 4.2. Training and image classification

366 In order to obtain the forest areas, the image before the Xynthia storm must be classified into  
 367 “forest” and “non-forest”. This is carried out following two steps: automatic extraction of forest pixels  
 368 based on the histogram, and by conducting a supervised classification of the two images before and  
 369 after the occurrence of the phenomenon.

##### 370 4.2.1. Automatic extraction of forest pixels

371 The forest pixels have been identified using the “dark object” approach [30] which involves the  
 372 delineation of the “forest peak”, based on a band local histogram (Figure 5). In the absence of non-  
 373 vegetated dark objects (which were masked previously), the forest pixels will be located to the left of  
 374 the histogram, while the first peak on the left will be considered the “peak forest”.

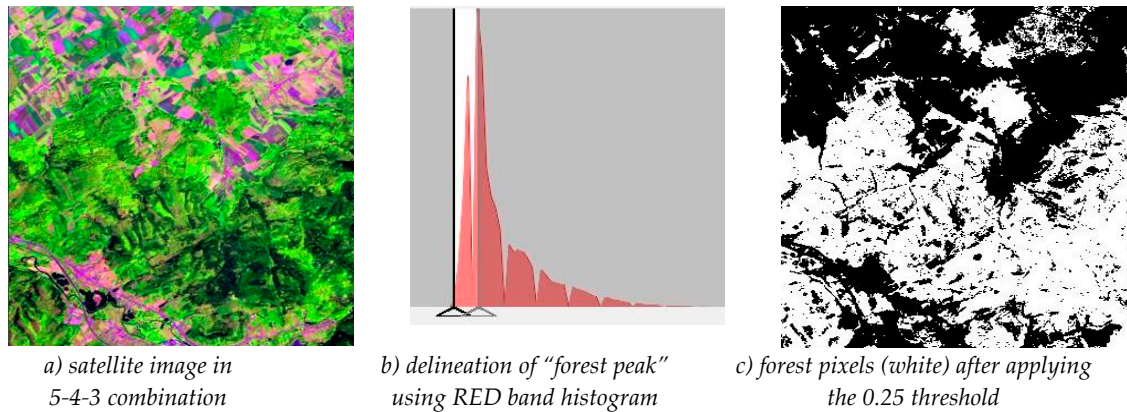
375 Huang et al. [30] recommends taking into account two major factors:

376 *i)* delineation should be done for a local image window, because this area will contain fewer classes  
 377 of land cover and the delineation of forest classes from other classes will be easier to achieve.

378 *ii)* selection should be made of the appropriate band to create the histogram which sets the basis for  
 379 class delineation.

380

381



382 **Figure 5.** The procedure for the delineation of forest pixels based on the histogram for the local image  
 383 window, (adapted after Huang et al. [30])

384 In order to determine whether pixels have been classified properly into forest and non-forest,  
 385 we have set samples of black pixels representing vegetation based on which we calculated the  
 386 Integrated Forest Index (IFI) [24, 30].

$$387 \quad IFI = \sqrt{\frac{1}{NB} \sum_{i=1}^{NB} \left( \frac{b_{pi} - \bar{b}_i}{SD_i} \right)^2} \quad (4)$$

388 where:

389  $\bar{b}_i$  and  $SD_i$  are the mean and standard deviation of forest training pixels within the image for band  
 390  $i$ ;

391  $b_{pi}$  is the band  $i$  spectral value for pixel  $p$ ;

392  $NB$  is the number of spectral bands.

393

394 Low IFIs values indicate a high probability of wooded areas, while high values indicate high  
 395 probability of other land cover categories. Certain dark pixels corresponding to crops may be  
 396 spectrally similar to pixels for forest areas, but will have IFIs values lower than the forest areas. To  
 397 eliminate them, it is necessary to set a threshold value, which separates the forest areas from the other  
 398 areas. For the present study, the threshold was set to 3, so pixels smaller than or equal to 3 are  
 399 considered as belonging to the wooded areas.

#### 400 4.2.2. Supervised classification

401 The general objective of the image classification procedure is to classify all the pixels from an  
 402 image in classes of ground cover or themes. The purpose of the classification in this study is to  
 403 complement the result of extracting forest pixels by means of the histogram. First of all, land cover  
 404 classes (water bodies), forest areas (conifers, mixed and deciduous trees), urban areas, pastures and  
 405 agricultural areas were established and the pixels were selected for the classification algorithm to  
 406 acknowledge the classes. After running the classification algorithm (Figure 6a), the resulting images  
 407 have been reclassified into forest areas and non-forest areas. Finally, following the classification of  
 408 both images from 2009 and 2010, the separation of the forest areas from the non-forest areas was  
 409 achieved (Figure 6b). This will be used in the end to obtain a change map for the two analysed  
 410 temporal frames.

411

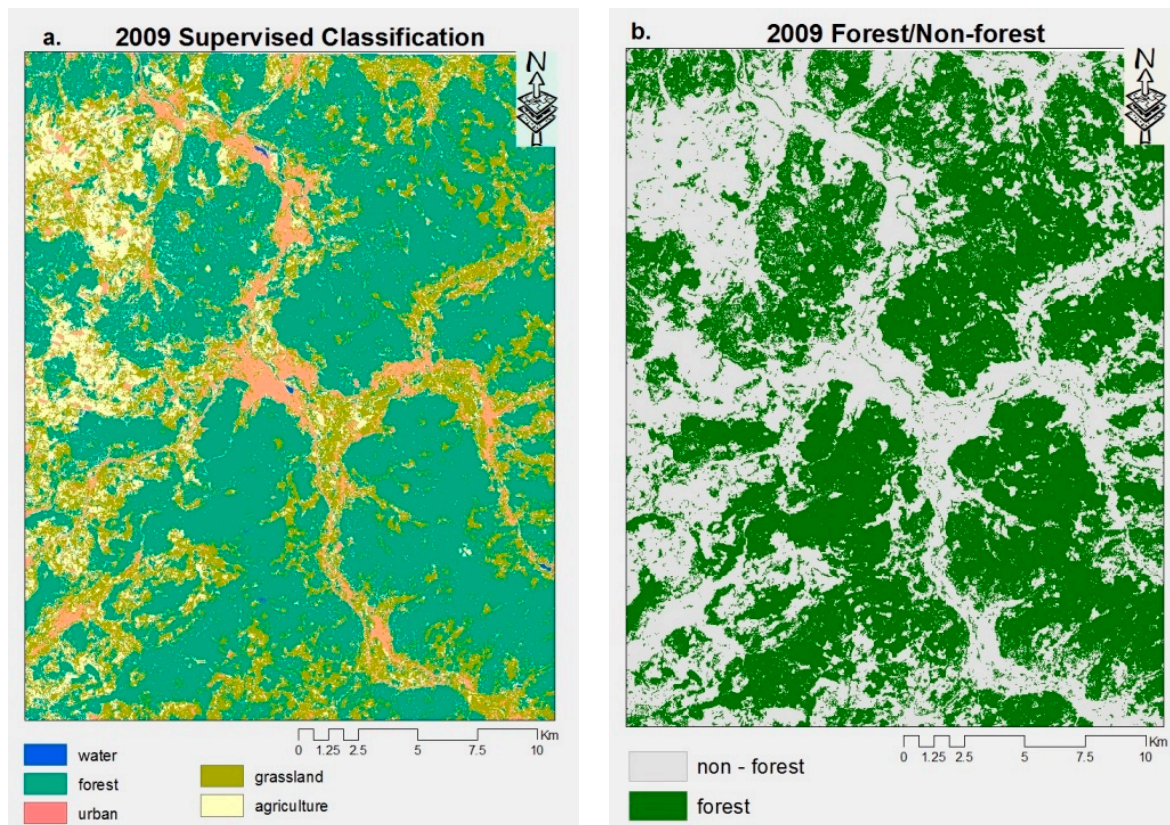


Figure 6. Supervised classification (a) and forest/non-forest classification (b).

#### 412 4.3. Forest Disturbance Detection

413 The detection of forest disturbed areas was carried out using the Disturbance Index (DI)  
 414 developed by Healey et al. [23] and applied by [24, 69-75]. DI was developed to highlight the spectral  
 415 signatures of non-vegetated areas associated with disturbance zones and to separate them from all  
 416 other spectral signatures of the forest areas. The procedure is based on a combination of bands  
 417 resulting from the Tasseled Cap Transformation, which reduces the six bands of Landsat TM image  
 418 (excluding the thermal band) into three bands that render brightness, greenness, and wetness.

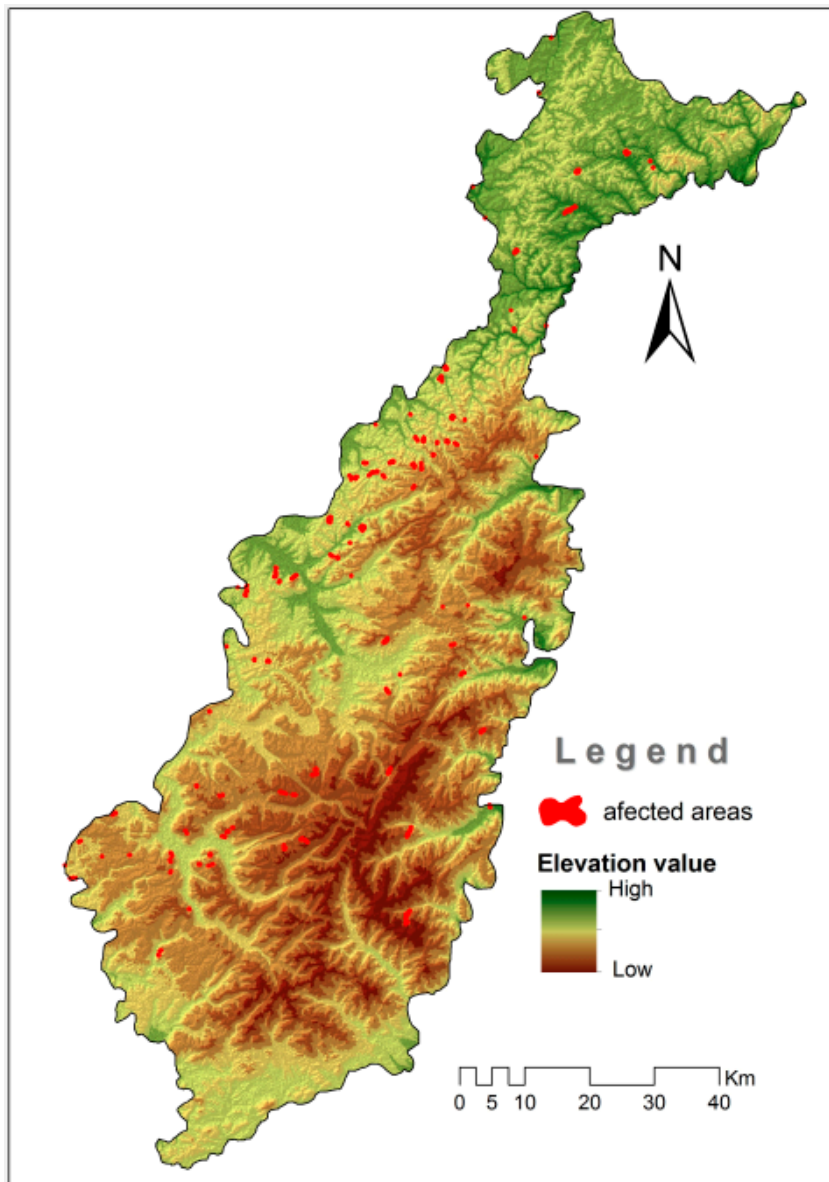
419 This index highlights the difference in spectral signatures and thus disturbed forest areas have  
 420 higher brightness values and lower values for greenness and wetness bands compared to  
 421 undisturbed forest areas. The index is calculated based on the formula:

$$422 \quad 423 \quad \text{DI} = \text{Br} - (\text{Gr} + \text{Wr}) \quad (5)$$

424 Where: Br, Gr, Wr are the Tasseled Cap bands, standardized (resized) around the scene's mean forest  
 425 value.

426  
 427 The result of the calculation is a single band, where positive values generally indicate areas with  
 428 disturbance. In order to separate the disturbed areas from the non-disturbed ones, it is necessary to  
 429 identify a limit threshold, depending on the environmental conditions in the studied area. In our case,  
 430 the value of  $\text{DI} = 2.5$  best identifies the areas affected by windthrows.

431 The last step involved the overlapping of the initial image classified as "forest areas" and "non-  
 432 forest areas" with the map derived from the DI calculation, and so we obtained a change map for the  
 433 forest area in the Vosges Mountains in 2009-2010 (Figure 7).



434

435

Figure 7. Areas affected by diffuse windthrow.

436 As seen in Figure 7, diffuse windthrows occur in the form of scattered polygons, or rather points,  
437 on the territory of the Vosges Mountains, some points being so small that they cannot be visually  
438 perceived at the scale of cartographic representation in the figure above. We identified 257 polygons  
439 (list available in Table S1: Polygons obtained after running the detection algorithm), affected by  
440 windthrows, with a total area of 229 ha. We attach additional material to indicate diffuse windthrow  
441 (Appendix A).

## 442 5. Results and discussions

443 In the algorithm we have developed, we included neither the object-based image analysis nor  
444 the segmentation procedures. We will explain next why we particularly made this decision.  
445 Segmentation techniques are recommended to detect possible changes, especially for high-resolution  
446 satellite imagery. Comparing the results obtained by the segmentation of the Landsat images with  
447 high-resolution images, it was revealed that Landsat results provide a low accuracy [76]. The classes  
448 are not well defined. The analysis is more difficult and requires a high user experience [77]. In  
449 addition to the resolution characteristics, there are other factors such as geomorphological structure,  
450 topography, and dead vegetation [78], that affect the applicability of segmentation on Landsat

451 images. The algorithm we propose is similar to the French methodology known as the “7-point  
452 method” [33]. However, this still includes different stages, proving to be effective in detecting diffuse  
453 windthrows based on Landsat images.

454 The difference between this method and the “7 points” method is given by the steps followed  
455 and the approaches used. The first difference is given by the satellite images used. This study is based  
456 on medium-resolution Landsat satellite images, while the “7 points” method uses high resolution  
457 images. In the “7 points” method, “pixel per pixel” is used in order to detect the changes. The same  
458 “pixel per pixel” approach was also used in this study, but it was applied to forest/non-forest images.  
459 The next stage in the “7 points” approach consisted in the segmentation of the disturbed areas. As  
460 Darwish et al. [76] stated, the segmentation techniques on the Landsat images emphasized the fact  
461 that the results provided a low accuracy. Therefore, this method is not recommended for medium  
462 resolution images. Instead, in this study we used the Disturbance Index to detect the affected areas.  
463 This index is calculated based on the bands obtained from the Tasseled Cap Transformation and it  
464 highlights the difference in spectral signatures. Thereby, the disturbed forest areas have higher  
465 brightness values and lower greenness and wetness values compared to undisturbed forest areas.

466 The last step in the “7 points method” is to integrate the results obtained by segmentation with  
467 the soil results. Thus, by classifying the disturbances produced, a map of damages was obtained. Due  
468 to lack of ground data, we have chosen to do a validation based on the error matrix. Thus, we have  
469 calculated the accuracy for the supervised classification into forest and non-forest categories, as well  
470 as for the map of changes in forest areas. This map was obtained by overlaying the two resulting  
471 maps (from the difference between the forest/non-forest image and the image resulting from the DI  
472 calculation). For validation, we overlapped the resulting polygons from change map on the 2009  
473 orthophotos and the 2010 RapidEye satellite image (Figure 9).

#### 474 5.1. Accuracy Assessment

475 To evaluate the quality of the analysis, we assessed the overall accuracy and the Kappa  
476 coefficient. Following the classification of the two images, the accuracy assessment was performed in  
477 two steps: a) the accuracy of supervised classification and of forest/non-forest classification and b)  
478 the accuracy of the forest change map.

479 To evaluate the accuracy of the supervised classification, we used 100 random points for each  
480 class we used. These points were manually labelled using Quickbird Google Earth and RapidEye  
481 high-resolution imagery [79]. These high-resolution images were used only for the confirmation and  
482 validation of the classification. Also, for results verification and validation purposes,  
483 orthophotoplans from 2009 were used, with a resolution of 2.5 and 5 m, available on [80].

484 The polygons resulting from the detection process were overlapped with the orthophotos to see  
485 whether there is vegetation in the detected areas. The result was summarized in an error matrix,  
486 while calculating the overall accuracy and the Kappa coefficient. Therefore, the accuracy assessment  
487 calculated for the forest/non-forest classification is given by the overall accuracy = 94.14% and by the  
488 Kappa coefficient = 0.92. The evaluation of the forest changes occurred between 2009 and 2010 was  
489 carried out based on a sample of 300 points. The previously defined samples considered as real  
490 elements in the field were used to calculate the error matrix, the overall accuracy, the kappa statistic  
491 and the user's and producer's accuracy for each class, as shown in Table 4.

492 For the change map we used three classes, namely *constant forest* (CF) that did not change in the  
493 two images, *disturbed areas* (D) and *other non-forest classes* (NF). The constant forest area is given by  
494 those areas that were represented by forest both in the *before Xynthia* storm image and in the *after*  
495 *Xynthia* image, while the areas with disturbances are those areas that were classified as forest in the  
496 *before Xynthia* image and that appeared as non-forest in the *after Xynthia* image. The overall accuracy  
497 obtained for the change map was high, i.e. 86%, and the value of the Kappa coefficient was 0.84. Also,  
498 the class represented by the constant forest had the user's and producer's accuracy higher than the  
499 disturbance class.

500

**Table 4.** The accuracy assessment calculated for the change map



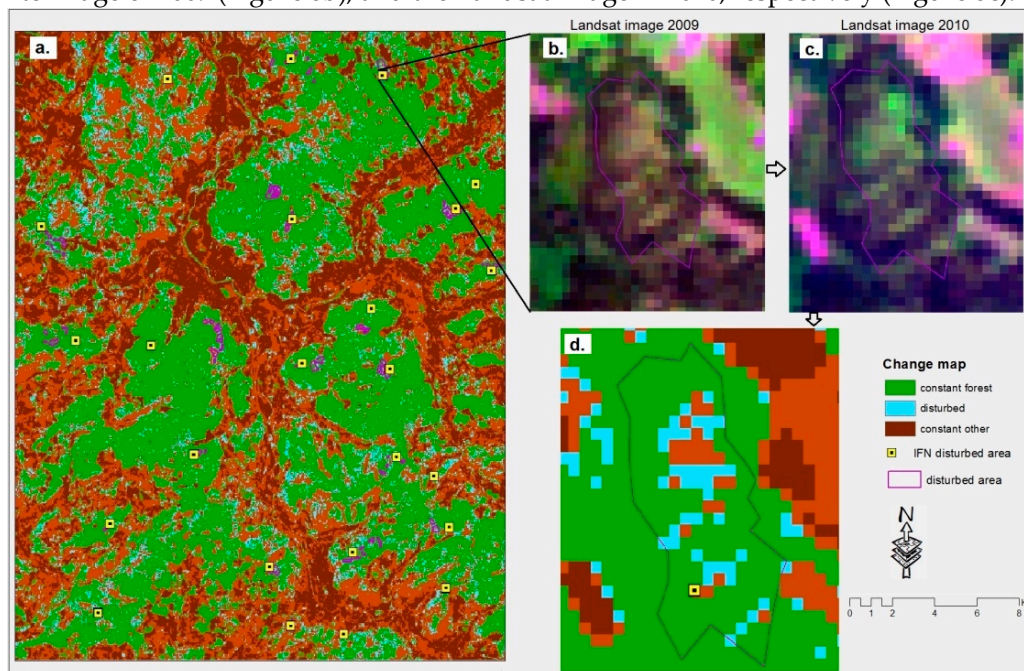
501

(CF=constant forest class; D=disturbance class; CNF=constant non-forest class)

Overall accuracy (%)	Kappa statistic	User's accuracy (%)			Producer's accuracy (%)		
		CF	D	CNF	CF	D	CNF
86	0.84	89.10	78	88	81	80	88.47

502 *5.2. Results validation*

503 Once the accuracy of the thematic data has been set, the validation of the results was the next  
 504 step. Detecting forest surface changes using satellite imagery is a difficult task and requires validation  
 505 using ground data. The validation was conducted based on disturbance data occurred in 2010 in the  
 506 mountains area (data available on [81], referring to all types of disturbances, not only windthrows),  
 507 on the cadastral forest plots for the two years (data available on [82], as well as on the orthophotos of  
 508 2009 and the high-resolution satellite imagery of 2010. For the final validation we used the change  
 509 map obtained previously and we combined it with data on disturbed forest areas, according to the  
 510 French National Forest Inventory (IFN). The resulting polygons during the detection process were  
 511 overlapped with the disturbed areas. Hence, we obtained a first validation of the results. Figure 8  
 512 highlights one of the polygons detected from the image processing, overlapped with the Landsat  
 513 satellite image of 2009 (Figure 8b), and the Landsat image in 2010, respectively (Figure 8c).

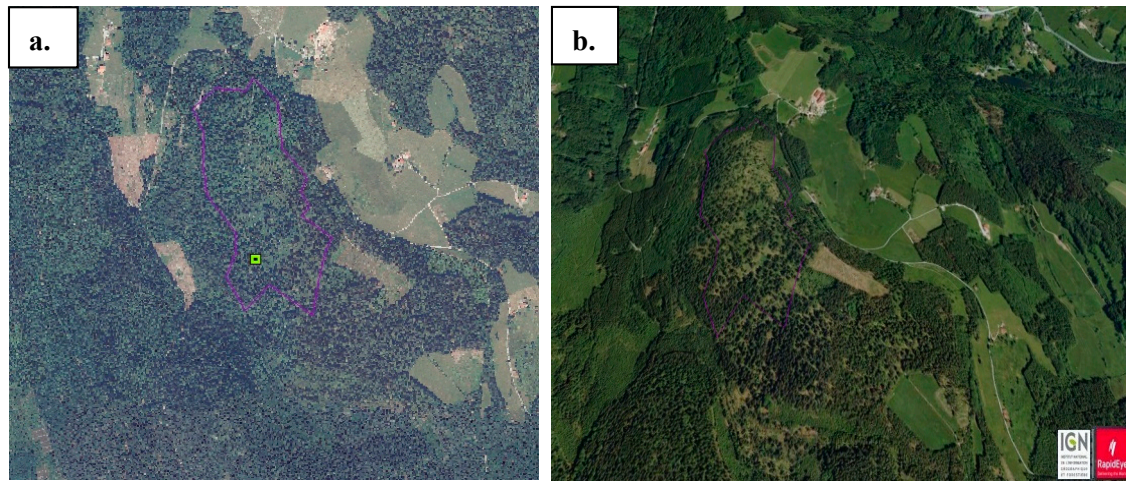


514

515 **Figure 8.** Forest change map (a) overlapped with the polygons resulting from the detection  
 516 process, as well as the points where windthrows occurred in 2010 (according to INF): one  
 517 polygon overlapped with the 2009 satellite image (b), and the 2010, respectively (c), and a  
 518 zoom on the same polygon (d).

519 Also, in order to obtain a picture of the “ground-truth”, this polygon was overlapped with the  
 520 orthophoto of 2009, and with the 2010 RapidEye high-resolution image (Figure 9), thus achieving a  
 521 new validation.

522

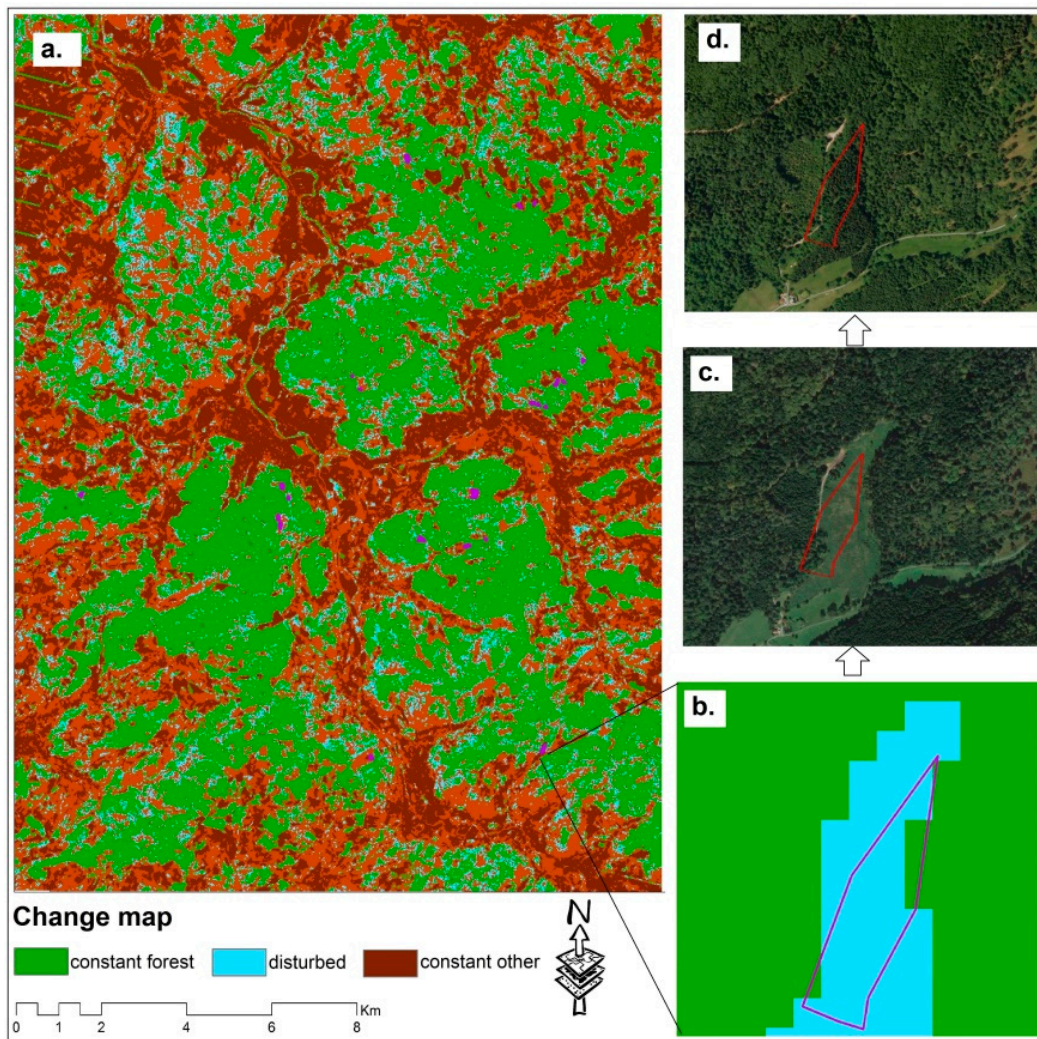


523 **Figure 9.** Overlapping a polygon extracted through the detection process with the 2009  
524 orthophoto (a) and with the satellite image in 2010 (b).

525 Another validation was carried out using high-resolution satellite imagery available in Google  
526 Earth. For an easier interpretation of the effect of the Xynthia storm, we zoomed out to a sample  
527 territory of 26.6 km x 20.5 km, i.e. 54,613 ha, which is in the centre of the Remiremont city (Figure 10).

528 Hence, Figure 10(b) highlights another polygon obtained as a result of the disturbed areas  
529 detection process. This polygon is superimposed on the change map (in raster format). In the  
530 windthrows detection phase, raster data were used which were subsequently converted into vector  
531 data in order to overlap the final results. By converting these images, a comparison between the  
532 results detected on raster format (blue colour) and vector representation (purple polygon) was  
533 achieved. The geometric effect of this polygon obtained by switching from raster format to vector  
534 format suggests a possible underestimation of the actual area damaged by the wind. Figure 10 (d)  
535 shows the image *before* the Xynthia storm, while Figure 10 (c) illustrates the forest state *after* the  
536 Xynthia storm.

537



538

539 **Figure 10.** The forest change map overlaid with the polygons resulting from the detection  
 540 process (a); zooming one polygon (b); the same polygon overlapped with the 2009 Goggle  
 541 Earth satellite image (c) and from 2010, respectively (d)

## 542 5. Conclusions

543 The tree windthrows caused by storms are much easier to detect by the authorities if they are  
 544 contiguous, compared to the diffuse or isolated ones. The diffuse windthrows occur in the temperate  
 545 zone at wind gusts of 100-140 km/h and their areas range between a few tens of square meters and  
 546 a few hectares, but they are very numerous, of several hundreds in the wooded mountain massifs. For  
 547 this reason, they are more difficult to detect, map and, obviously, it is much more difficult to  
 548 characterize the extent of the damage. However, the detection of changes occurred as a result of the  
 549 diffuse windthrows, even if they are several hundred, is also important in order to set the spatial and  
 550 temporal rehabilitation and forest management trends. In this regard, this paper presents a rapid  
 551 procedure for the detection of the diffuse windthrows based on low cost images, knowing that certain  
 552 sensors cannot be accessed without significant investments. Our application is based on the study of  
 553 effects caused by the Xynthia storm in the Vosges Mountains, on 28 February 2010.

554 The results of this research highlight the usefulness of the Landsat satellite imagery, more easily  
 555 to access than other types of images for the analysis and detection of windthrows. The detection of  
 556 areas damaged by the Xynthia storm by applying the pixels delineation method based on the  
 557 histogram enabled us to automatically delimit the forest pixels from the non-forest ones, thus  
 558 reducing the working time. The Disturbance Index enabled the more accurate delineation of the  
 559 affected areas.

560 The classification of the area into forest and non-forest increases the precision level for the  
561 detection of affected areas. The Tasseled Cap Transformation and the calculation of the Disturbance  
562 Index enable us to highlight the affected areas. The accuracy assessment of the results obtained for  
563 the change map was high (86 % overall accuracy and the value of the Kappa coefficient was 0.84).  
564 Also, the constant forest class in the two images, before and after the phenomenon, had the user's  
565 and producer's accuracy higher than the disturbance class, i.e. 89.10% and 81% respectively,  
566 compared to 78% and 80%.

567 The spatial analysis enabled us to highlight the most affected areas, resulting in 257 affected  
568 polygons, totalling 229 ha. The largest polygon is 13 ha, located east from the Grand-Soldat hamlet,  
569 Abreschviller village, department of Moselle. Moreover, following the analysis conducted, it was  
570 concluded that most of the affected polygons had a predominantly coniferous vegetation  
571 composition (75%), with slopes facing N, NW and W. For validation purposes, high-resolution  
572 images and orthophotoplans taken before and after the storm were used. The error matrix was  
573 calculated, achieving an overall accuracy of 86%, which reveals that our methodology adapted for  
574 low cost image resources, can be used for the rapid detection of diffuse windthrows in the temperate  
575 zone.

#### 576 **Supplementary Materials:**

577 **Table S1.** Polygons obtained after running the detection algorithm.

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581 **Author Contributions:** I. Haidu and P. Furtuna conceived and designed the experiments; P. Furtuna performed  
582 the experiments; I. Haidu and S. Lébaut analyzed the data; P. Furtuna, I.Haidu and S. Lébaut wrote the paper.

583 **Conflicts of Interest:** The authors declare no conflict of interest.

## 584 **Appendix A**

585 The largest polygon has an area of 13 ha (450-550 m altitude), East of the Grand-Soldat hamlet,  
586 Abreschviller village, department of Moselle. In the neighbouring Southern village of Saint-Quirin,  
587 the second disturbed polygon is the size of 9.2 ha (450-330 m altitude). Also in Moselle there is a 7.7  
588 ha polygon in the Northern Vosges Regional Natural Park, North of Baerenthal and a 7.9 hectare  
589 polygon South-West of Mouterhouse. In the department of Vosges there is a 6.1 hectare polygon  
590 South of Arrentès-de-Corcieux. In the department of Haut-Rhin in Alsace there is a 7.5 ha disturbed  
591 area North-West of Lake Grand Ballon, on the territory of the Lauteenbach-Zell village.

592 Following the conducted analysis, it was found that most of the affected polygons had  
593 predominantly coniferous vegetation (75%), at an average altitude of 950 m, with N-, NW- and W-  
594 facing slopes. Of the 257 polygons, only 7 have more than 5 hectares of disturbed area, but they are  
595 51.12 % of the total windthrow area. 56 polygons range from 1 to 5 ha and the remaining 194 polygons  
596 are under 1 ha. The smallest affected polygon detected by the methodology presented above and  
597 based on the limited data images approach is 0.09 ha. This is much better than the detection threshold  
598 based on 1 ha of satellite imagery that was used to assess the damages caused by the 1999 storms [83].

599 The large number of small polygons detected, 194 polygons under 1 ha, come as a result of the  
600 particularities of interaction between high wind speeds, over 130 km/h and the relief features of the  
601 Vosges Mountains. Generally, the affected polygons appear on the slopes facing the direction of the  
602 Xynthia storm. At the escalation of the slopes, the speed of the wind gusts accelerated resulting in an  
603 effect similar to bearing, resulting in a greater pressure exerted on the forest cover area.

## 604 **References**

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799

**800 Supplementary Materials:****801 Table S1.** Polygons obtained after running the detection algorithm.



	OBJCTID	Id	Shap_Lg	Area_m <sup>2</sup>	Ara_ha	X (decimal degrees)	Y ( decimal degrees)	Longitude	Latitude
1	381	381	327.66	4921.4	0.4921	7.347278	49.147080	7° 20' 50.202"	49° 8' 49.486"
2	2461	2461	269.30	3290.6	0.3291	7.323385	49.070599	7° 19' 24.184"	49° 4' 14.156"
3	7037	7037	1454.88	77313.3	7.7313	7.509725	48.991177	7° 30' 35.010"	48° 59' 28.237"
4	7462	7462	169.76	1228.8	0.1229	7.515414	48.989874	7° 30' 55.490"	48° 59' 23.547"
5	7482	7482	120.00	900.0	0.0900	7.514831	48.989579	7° 30' 53.391"	48° 59' 22.484"
6	7601	7601	256.60	2963.2	0.2963	7.511610	48.988011	7° 30' 41.797"	48° 59' 16.838"
7	8227	8227	219.57	2034.1	0.2034	7.560925	48.979285	7° 33' 39.328"	48° 58' 45.428"
8	8925	8925	169.77	1229.0	0.1229	7.567033	48.970118	7° 34' 1.319"	48° 58' 12.423"
9	9353	9353	213.01	2132.2	0.2132	7.410459	48.961315	7° 24' 37.651"	48° 57' 40.735"
10	9363	9363	1748.00	78665.9	7.8666	7.407721	48.963144	7° 24' 27.794"	48° 57' 47.317"
11	10361	10361	224.28	2418.1	0.2418	7.188378	48.938636	7° 11' 18.162"	48° 56' 19.089"
12	11771	11771	489.00	10211.5	1.0211	7.404978	48.913743	7° 24' 17.922"	48° 54' 49.473"
13	11823	11823	432.87	8105.0	0.8105	7.400416	48.912271	7° 24' 1.499"	48° 54' 44.177"
14	11863	11863	224.28	2418.1	0.2418	7.396563	48.910951	7° 23' 47.627"	48° 54' 39.425"
15	11884	11884	224.28	2418.1	0.2418	7.394142	48.909838	7° 23' 38.911"	48° 54' 35.418"
16	11936	11936	213.01	2132.2	0.2132	7.388374	48.908921	7° 23' 18.148"	48° 54' 32.115"
17	11937	11937	362.36	7525.5	0.7526	7.392273	48.909277	7° 23' 32.181"	48° 54' 33.398"
18	11975	11975	120.00	900.0	0.0900	7.395239	48.908091	7° 23' 42.861"	48° 54' 29.127"
19	11992	11992	172.66	1046.0	0.1046	7.394726	48.907814	7° 23' 41.014"	48° 54' 28.130"
20	12014	12014	322.64	4991.2	0.4991	7.388727	48.907413	7° 23' 19.416"	48° 54' 26.686"
21	12063	12063	268.59	3297.5	0.3298	7.387090	48.906768	7° 23' 13.525"	48° 54' 24.364"
22	12084	12084	170.22	1214.9	0.1215	7.385695	48.906354	7° 23' 8.502"	48° 54' 22.875"
23	12205	12205	180.00	1800.0	0.1800	7.382662	48.904542	7° 22' 57.582"	48° 54' 16.350"
24	12453	12453	120.00	900.0	0.0900	7.216358	48.895476	7° 12' 58.889"	48° 53' 43.715"
25	13489	13489	169.77	1229.0	0.1229	7.284117	48.852362	7° 17' 2.823"	48° 51' 8.504"
26	13508	13508	322.66	4274.5	0.4275	7.282140	48.851920	7° 16' 55.705"	48° 51' 6.912"

27	13525	13525	376.43	5786.9	0.5787	7.285366	48.850807	7° 17' 7.317"	48° 51' 2.905"
28	13540	13540	267.12	2878.8	0.2879	7.281793	48.849646	7° 16' 54.453"	48° 50' 58.727"
29	13556	13556	120.00	900.0	0.0900	7.279782	48.848400	7° 16' 47.215"	48° 50' 54.239"
30	13559	13559	120.00	900.0	0.0900	7.280200	48.848136	7° 16' 48.719"	48° 50' 53.289"
31	13568	13568	120.00	900.0	0.0900	7.280618	48.847872	7° 16' 50.224"	48° 50' 52.340"
32	14882	14882	120.00	900.0	0.0900	7.275157	48.768712	7° 16' 30.565"	48° 46' 7.363"
33	15198	15198	265.37	3187.2	0.3187	7.349408	48.748613	7° 20' 57.868"	48° 44' 55.007"
34	15277	15277	209.69	1972.1	0.1972	7.281863	48.743617	7° 16' 54.708"	48° 44' 37.022"
35	15289	15289	360.00	7200.0	0.7200	7.282939	48.740911	7° 16' 58.580"	48° 44' 27.279"
36	15298	15298	334.52	6612.2	0.6612	7.282392	48.742647	7° 16' 56.610"	48° 44' 33.527"
37	16608	16608	833.26	32473.6	3.2474	7.140469	48.687928	7° 8' 25.688"	48° 41' 16.542"
38	16672	16672	718.37	18109.8	1.8110	7.142110	48.685686	7° 8' 31.594"	48° 41' 8.470"
39	16674	16674	299.45	4802.4	0.4802	7.143827	48.685477	7° 8' 37.779"	48° 41' 7.716"
40	16938	16938	120.00	900.0	0.0900	7.132053	48.674985	7° 7' 55.392"	48° 40' 29.944"
41	16939	16939	264.55	4093.0	0.4093	7.132919	48.675171	7° 7' 58.509"	48° 40' 30.615"
42	16963	16963	643.55	10507.4	1.0507	7.130703	48.674397	7° 7' 50.530"	48° 40' 27.830"
43	16981	16981	169.77	1228.9	0.1229	7.132906	48.673229	7° 7' 58.463"	48° 40' 23.623"
44	17028	17028	661.69	15097.1	1.5097	7.128864	48.671886	7° 7' 43.911"	48° 40' 18.788"
45	17106	17106	789.71	12482.8	1.2483	7.132993	48.670633	7° 7' 58.775"	48° 40' 14.278"
46	17144	17144	285.23	3842.1	0.3842	7.134045	48.668716	7° 8' 2.562"	48° 40' 7.377"
47	19017	19017	256.11	3961.9	0.3962	7.069609	48.621487	7° 4' 10.592"	48° 37' 17.354"
48	19411	19411	1777.12	129798.2	12.9798	7.157301	48.618670	7° 9' 26.284"	48° 37' 7.213"
49	19458	19458	212.17	2112.0	0.2112	7.183347	48.615975	7° 11' 0.048"	48° 36' 57.511"
50	19802	19802	120.00	900.0	0.0900	6.997850	48.606063	6° 59' 52.259"	48° 36' 21.825"
51	20815	20815	163.00	1255.7	0.1256	7.082725	48.589829	7° 4' 57.811"	48° 35' 23.383"
52	20860	20860	412.02	6571.0	0.6571	7.081275	48.589519	7° 4' 52.591"	48° 35' 22.268"
53	20890	20890	300.00	5400.0	0.5400	7.082554	48.588611	7° 4' 57.193"	48° 35' 19.000"

54	20948	20948	163.00	1255.7	0.1256	7.083998	48.587691	7° 5' 2.393"	48° 35' 15.686"
55	21005	21005	120.00	900.0	0.0900	7.085278	48.586497	7° 5' 7.001"	48° 35' 11.390"
56	21043	21043	120.00	900.0	0.0900	7.147099	48.586969	7° 8' 49.555"	48° 35' 13.089"
57	21076	21076	317.56	5114.4	0.5114	7.086101	48.585656	7° 5' 9.964"	48° 35' 8.363"
58	21155	21155	224.98	2781.7	0.2782	7.147809	48.585483	7° 8' 52.111"	48° 35' 7.738"
59	21213	21213	120.00	900.0	0.0900	7.146374	48.584528	7° 8' 46.947"	48° 35' 4.302"
60	21226	21226	200.25	2515.0	0.2515	7.127448	48.584163	7° 7' 38.813"	48° 35' 2.988"
61	21241	21241	256.11	3961.9	0.3962	7.149951	48.584210	7° 8' 59.823"	48° 35' 3.156"
62	21267	21267	6439.64	328767.0	9.1852	7.098719	48.587042	7° 5' 55.387"	48° 35' 13.352"
63	21274	21274	300.00	5400.0	0.5400	7.127102	48.583137	7° 7' 37.568"	48° 34' 59.292"
64	21277	21277	223.00	3055.7	0.3056	7.164146	48.583599	7° 9' 50.927"	48° 35' 0.955"
65	21452	21452	550.10	12540.6	1.2541	7.168475	48.581431	7° 10' 6.508"	48° 34' 53.153"
66	22356	22356	120.00	900.0	0.0900	7.121400	48.566849	7° 7' 17.042"	48° 34' 0.658"
67	22443	22443	577.47	15575.5	1.5575	7.119109	48.566457	7° 7' 8.794"	48° 33' 59.245"
68	22551	22551	120.00	900.0	0.0900	7.334484	48.567161	7° 20' 4.143"	48° 34' 1.779"
69	22958	22958	430.87	9278.3	0.9278	7.035810	48.556293	7° 2' 8.916"	48° 33' 22.654"
70	23024	23024	480.00	10800.0	1.0800	7.035847	48.555030	7° 2' 9.050"	48° 33' 18.107"
71	23038	23038	169.76	1228.8	0.1229	7.031971	48.554678	7° 1' 55.096"	48° 33' 16.842"
72	23094	23094	954.76	33320.0	3.3320	6.978291	48.552374	6° 58' 41.846"	48° 33' 8.547"
73	23116	23116	823.73	26656.1	2.6656	7.029786	48.553955	7° 1' 47.230"	48° 33' 14.238"
74	23143	23143	349.59	5576.1	0.5576	6.975188	48.553122	6° 58' 30.676"	48° 33' 11.238"
75	23176	23176	163.00	1255.7	0.1256	7.078820	48.553326	7° 4' 43.752"	48° 33' 11.974"
76	23187	23187	224.28	2418.2	0.2418	7.077782	48.553047	7° 4' 40.016"	48° 33' 10.970"
77	23220	23220	300.00	5400.0	0.5400	7.075992	48.552469	7° 4' 33.572"	48° 33' 8.889"
78	23288	23288	354.87	6187.5	0.6187	7.079457	48.551531	7° 4' 46.044"	48° 33' 5.512"
79	23302	23302	163.00	1255.7	0.1256	7.082152	48.551222	7° 4' 55.747"	48° 33' 4.400"
80	23380	23380	168.01	1393.6	0.1394	7.095778	48.549970	7° 5' 44.801"	48° 32' 59.891"

81	23389	23389	438.23	8861.8	0.8862	7.079972	48.549914	7° 4' 47.899"	48° 32' 59.690"
82	23458	23458	277.89	3387.5	0.3387	7.081279	48.548692	7° 4' 52.604"	48° 32' 55.291"
83	23526	23526	1684.01	53471.8	5.3472	7.095052	48.550939	7° 5' 42.189"	48° 33' 3.380"
84	23607	23607	621.52	14512.3	1.4512	7.095847	48.546374	7° 5' 45.050"	48° 32' 46.947"
85	23827	23827	2436.83	166363.4	3.8650	7.002467	48.541006	7° 0' 8.881"	48° 32' 27.620"
86	23843	23843	522.95	13622.9	1.3623	6.994330	48.540124	6° 59' 39.587"	48° 32' 24.445"
87	24072	24072	653.42	16176.8	1.6177	6.987321	48.536292	6° 59' 14.355"	48° 32' 10.652"
88	24075	24075	227.61	1857.7	0.1858	7.015204	48.536142	7° 0' 54.734"	48° 32' 10.112"
89	24091	24091	224.28	2418.2	0.2418	6.945620	48.534553	6° 56' 44.233"	48° 32' 4.389"
90	24116	24116	168.12	1349.7	0.1350	7.018118	48.535307	7° 1' 5.227"	48° 32' 7.105"
91	24196	24196	266.95	3199.2	0.3199	7.018890	48.533683	7° 1' 8.003"	48° 32' 1.259"
92	24226	24226	328.62	5129.5	0.5130	6.951903	48.531878	6° 57' 6.850"	48° 31' 54.762"
93	24286	24286	978.26	42216.8	4.2217	6.960387	48.531902	6° 57' 37.393"	48° 31' 54.848"
94	24322	24322	170.22	1214.9	0.1215	6.949084	48.529375	6° 56' 56.704"	48° 31' 45.751"
95	24740	24740	257.66	3102.6	0.3103	7.081205	48.522858	7° 4' 52.337"	48° 31' 22.288"
96	24906	24906	276.77	3300.4	0.3300	7.079757	48.520636	7° 4' 47.125"	48° 31' 14.289"
97	24963	24963	120.00	900.0	0.0900	7.078473	48.519177	7° 4' 42.502"	48° 31' 9.036"
98	27756	27756	390.60	6298.4	0.6298	6.908963	48.476141	6° 54' 32.266"	48° 28' 34.108"
99	27787	27787	411.21	9407.9	0.9408	6.906792	48.475905	6° 54' 24.452"	48° 28' 33.257"
100	28074	28074	1883.34	85002.9	4.1185	6.906583	48.473189	6° 54' 23.699"	48° 28' 23.480"
101	28208	28208	286.43	4871.0	0.4871	6.904374	48.470593	6° 54' 15.746"	48° 28' 14.134"
102	28330	28330	521.79	10777.3	1.0777	6.907999	48.469531	6° 54' 28.797"	48° 28' 10.312"
103	28533	28533	328.28	4408.7	0.4409	6.944120	48.468323	6° 56' 38.832"	48° 28' 5.964"
104	28662	28662	306.17	4614.9	0.4615	6.945653	48.467190	6° 56' 44.352"	48° 28' 1.885"
105	28837	28837	270.85	3900.6	0.3901	6.976134	48.465983	6° 58' 34.082"	48° 27' 57.538"
106	28967	28967	302.67	5076.5	0.5077	6.973708	48.464862	6° 58' 25.349"	48° 27' 53.503"
107	28969	28969	300.00	5400.0	0.5400	6.980086	48.464589	6° 58' 48.309"	48° 27' 52.520"

108	29170	29170	485.16	14181.3	1.4181	6.978799	48.462471	6° 58' 43.676"	48° 27' 44.894"
109	29222	29222	684.90	22449.5	2.2450	6.972086	48.462778	6° 58' 19.511"	48° 27' 46.001"
110	29387	29387	324.64	5958.0	0.5958	6.977524	48.460374	6° 58' 39.088"	48° 27' 37.347"
111	29522	29522	172.66	1046.0	0.1046	6.975760	48.458542	6° 58' 32.736"	48° 27' 30.751"
112	31127	31127	169.76	1228.8	0.1229	6.950751	48.441517	6° 57' 2.705"	48° 26' 29.461"
113	32858	32858	360.00	7200.0	0.7200	6.910702	48.424617	6° 54' 38.526"	48° 25' 28.621"
114	33039	33039	501.15	10310.9	1.0311	6.912671	48.423554	6° 54' 45.617"	48° 25' 24.794"
115	33117	33117	406.52	5990.2	0.5990	6.915411	48.422283	6° 54' 55.480"	48° 25' 20.219"
116	33207	33207	163.00	1255.7	0.1256	6.925611	48.421648	6° 55' 32.198"	48° 25' 17.932"
117	33408	33408	211.92	2085.1	0.2085	6.926289	48.419724	6° 55' 34.640"	48° 25' 11.005"
118	35168	35168	579.26	18669.7	1.8670	6.798052	48.404261	6° 47' 52.988"	48° 24' 15.341"
119	35893	35893	428.15	10147.4	1.0147	6.797606	48.398554	6° 47' 51.382"	48° 23' 54.795"
120	36245	36245	224.28	2418.2	0.2418	6.840897	48.395059	6° 50' 27.231"	48° 23' 42.211"
121	36312	36312	300.00	5400.0	0.5400	6.798424	48.395126	6° 47' 54.326"	48° 23' 42.452"
122	36318	36318	243.14	3019.8	0.3020	6.839625	48.394567	6° 50' 22.651"	48° 23' 40.440"
123	36505	36505	212.18	2112.1	0.2112	6.955297	48.396221	6° 57' 19.068"	48° 23' 46.395"
124	36598	36598	675.47	23152.2	2.3152	6.797437	48.393078	6° 47' 50.773"	48° 23' 35.080"
125	36630	36630	322.65	4785.1	0.4785	6.836460	48.393209	6° 50' 11.255"	48° 23' 35.554"
126	36663	36663	300.00	5400.0	0.5400	6.795116	48.391958	6° 47' 42.417"	48° 23' 31.049"
127	36893	36893	316.54	5611.9	0.5612	6.834163	48.391695	6° 50' 2.986"	48° 23' 30.103"
128	37125	37125	439.35	9668.5	0.9669	6.831618	48.390070	6° 49' 53.826"	48° 23' 24.251"
129	37457	37457	120.00	900.0	0.0900	6.807143	48.385575	6° 48' 25.716"	48° 23' 8.070"
130	37496	37496	120.00	900.0	0.0900	6.806750	48.385298	6° 48' 24.300"	48° 23' 7.072"
131	37674	37674	733.46	16331.9	1.6332	6.805255	48.385085	6° 48' 18.919"	48° 23' 6.307"
132	38162	38162	120.00	900.0	0.0900	6.738969	48.378587	6° 44' 20.287"	48° 22' 42.911"
133	38311	38311	120.00	900.0	0.0900	6.737814	48.377214	6° 44' 16.130"	48° 22' 37.971"
134	38421	38421	120.00	900.0	0.0900	6.720050	48.375784	6° 43' 12.182"	48° 22' 32.821"

135	38734	38734	120.00	900.0	0.0900	6.738386	48.373447	6° 44' 18.190"	48° 22' 24.408"
136	38946	38946	169.77	1229.0	0.1229	6.739053	48.371588	6° 44' 20.591"	48° 22' 17.718"
137	39216	39216	603.36	13616.3	1.3616	6.737833	48.369714	6° 44' 16.198"	48° 22' 10.969"
138	39657	39657	170.22	1214.9	0.1215	6.734896	48.365836	6° 44' 5.626"	48° 21' 57.009"
139	39784	39784	410.27	7473.3	0.7473	6.737050	48.365014	6° 44' 13.381"	48° 21' 54.050"
140	41319	41319	120.00	900.0	0.0900	7.199109	48.359451	7° 11' 56.791"	48° 21' 34.025"
141	41613	41613	168.12	1349.7	0.1350	7.146976	48.356314	7° 8' 49.112"	48° 21' 22.732"
142	43190	43190	120.00	900.0	0.0900	7.317063	48.344233	7° 19' 1.429"	48° 20' 39.240"
143	46284	46284	212.18	2112.1	0.2112	7.033681	48.311023	7° 2' 1.250"	48° 18' 39.684"
144	46527	46527	598.96	14064.8	1.4065	7.032518	48.309014	7° 1' 57.066"	48° 18' 32.450"
145	46762	46762	1328.11	54443.6	3.0803	7.029074	48.306753	7° 1' 44.667"	48° 18' 24.310"
146	46825	46825	907.12	24968.1	0.9474	7.026662	48.305276	7° 1' 35.982"	48° 18' 18.994"
147	46919	46919	168.01	1393.6	0.1394	7.173274	48.305336	7° 10' 23.786"	48° 18' 19.211"
148	47124	47124	528.63	15167.4	1.5167	7.166364	48.303774	7° 9' 58.910"	48° 18' 13.588"
149	47204	47204	360.00	7200.0	0.7200	6.700044	48.293733	6° 42' 0.158"	48° 17' 37.439"
150	48931	48931	990.36	27239.2	1.7510	6.758676	48.276533	6° 45' 31.232"	48° 16' 35.518"
151	49079	49079	662.65	16955.6	1.6956	6.786183	48.275179	6° 47' 10.259"	48° 16' 30.643"
152	49080	49080	265.37	3187.2	0.3187	6.789455	48.274633	6° 47' 22.038"	48° 16' 28.680"
153	50527	50527	120.00	900.0	0.0900	7.190664	48.266198	7° 11' 26.391"	48° 15' 58.311"
154	50528	50528	233.55	3314.8	0.3315	7.192318	48.266298	7° 11' 32.343"	48° 15' 58.673"
155	50560	50560	505.34	12019.4	1.2019	7.194604	48.266396	7° 11' 40.575"	48° 15' 59.027"
156	50730	50730	265.37	3187.2	0.3187	7.189708	48.264628	7° 11' 22.950"	48° 15' 52.662"
157	50871	50871	348.02	6707.5	0.6708	7.061401	48.261315	7° 3' 41.043"	48° 15' 40.735"
158	50873	50873	355.93	6448.4	0.6448	7.188392	48.263273	7° 11' 18.211"	48° 15' 47.784"
159	53148	53148	227.83	1949.7	0.1950	7.033794	48.241288	7° 2' 1.657"	48° 14' 28.638"
160	53287	53287	698.67	14754.4	1.4754	7.034697	48.239654	7° 2' 4.909"	48° 14' 22.753"
161	53390	53390	251.91	3318.7	0.3319	7.036319	48.238000	7° 2' 10.750"	48° 14' 16.799"

162	53446	53446	168.13	1349.9	0.1350	7.039235	48.235648	7° 2' 21.244"	48° 14' 8.334"
163	53472	53472	371.44	5772.5	0.5772	7.037205	48.237221	7° 2' 13.939"	48° 14' 13.997"
164	53591	53591	168.02	1393.7	0.1394	7.038172	48.236322	7° 2' 17.419"	48° 14' 10.758"
165	56532	56532	1858.75	73516.3	0.5567	6.669043	48.202887	6° 40' 8.556"	48° 12' 10.392"
166	59374	59374	170.22	1215.0	0.1215	7.239241	48.188421	7° 14' 21.269"	48° 11' 18.316"
167	59661	59661	637.30	24506.0	2.4506	7.236356	48.186760	7° 14' 10.881"	48° 11' 12.334"
168	59763	59763	352.86	5938.6	0.5939	7.233649	48.185838	7° 14' 1.138"	48° 11' 9.017"
169	59832	59832	224.27	2418.1	0.2418	7.238307	48.187866	7° 14' 17.904"	48° 11' 16.319"
170	59855	59855	212.17	2112.0	0.2112	7.232139	48.184876	7° 13' 55.701"	48° 11' 5.554"
171	59999	59999	212.17	2112.0	0.2112	7.232580	48.183803	7° 13' 57.286"	48° 11' 1.691"
172	65019	65019	1299.96	60812.4	6.0812	6.892683	48.126341	6° 53' 33.660"	48° 7' 34.827"
173	66819	66819	120.00	900.0	0.0900	7.046643	48.130768	7° 2' 47.914"	48° 7' 50.766"
174	66870	66870	180.00	1800.0	0.1800	7.046255	48.130357	7° 2' 46.519"	48° 7' 49.284"
175	66952	66952	120.00	900.0	0.0900	7.045475	48.129669	7° 2' 43.710"	48° 7' 46.807"
176	67152	67152	240.00	3600.0	0.3600	7.044302	48.127831	7° 2' 39.488"	48° 7' 40.191"
177	67234	67234	390.24	5818.0	0.5818	7.044891	48.128745	7° 2' 41.609"	48° 7' 43.481"
178	67430	67430	335.42	4966.8	0.4967	7.043572	48.126814	7° 2' 36.861"	48° 7' 36.529"
179	67497	67497	240.00	2700.0	0.2700	7.043221	48.125311	7° 2' 35.597"	48° 7' 31.121"
180	67551	67551	180.00	1800.0	0.1800	7.042431	48.124893	7° 2' 32.751"	48° 7' 29.615"
181	67582	67582	224.28	2418.2	0.2418	7.047014	48.131375	7° 2' 49.251"	48° 7' 52.951"
182	67585	67585	224.28	2418.2	0.2418	7.043302	48.125599	7° 2' 35.886"	48° 7' 32.155"
183	67652	67652	267.93	3090.3	0.3090	7.042302	48.123969	7° 2' 32.288"	48° 7' 26.287"
184	67685	67685	163.00	1255.7	0.1256	6.895007	48.121207	6° 53' 42.026"	48° 7' 16.344"
185	67772	67772	120.00	900.0	0.0900	6.893437	48.120503	6° 53' 36.375"	48° 7' 13.811"
186	67898	67898	219.57	2034.2	0.2034	6.887958	48.119675	6° 53' 16.650"	48° 7' 10.830"
187	67931	67931	169.76	1228.8	0.1229	6.884588	48.119380	6° 53' 4.515"	48° 7' 9.769"
188	70038	70038	1846.30	84529.5	2.1201	6.646952	48.099448	6° 38' 49.029"	48° 5' 58.011"

189	70760	70760	644.05	14818.3	1.4818	6.821553	48.094559	6° 49' 17.591"	48° 5' 40.413"
190	70899	70899	347.76	5710.5	0.5710	6.828641	48.093164	6° 49' 43.106"	48° 5' 35.390"
191	70981	70981	217.54	2316.4	0.2316	6.832718	48.092224	6° 49' 57.786"	48° 5' 32.005"
192	71079	71079	312.89	3487.2	0.3487	6.701415	48.087717	6° 42' 5.093"	48° 5' 15.780"
193	71084	71084	168.13	1349.9	0.1350	6.846103	48.091283	6° 50' 45.969"	48° 5' 28.617"
194	71133	71133	318.43	5590.2	0.5590	6.851443	48.091051	6° 51' 5.195"	48° 5' 27.782"
195	71558	71558	162.99	1255.7	0.1256	6.694672	48.087413	6° 41' 40.819"	48° 5' 14.687"
196	71593	71593	213.01	2132.1	0.2132	6.695531	48.086563	6° 41' 43.911"	48° 5' 11.626"
197	72632	72632	375.80	7542.6	0.7543	7.253864	48.083853	7° 15' 13.910"	48° 5' 1.872"
198	72954	72954	120.00	900.0	0.0900	7.254784	48.080673	7° 15' 17.224"	48° 4' 50.424"
199	74046	74046	560.86	15661.7	1.5662	6.480911	48.058205	6° 28' 51.281"	48° 3' 29.539"
200	74214	74214	336.55	5010.0	0.5010	6.474940	48.055932	6° 28' 29.783"	48° 3' 21.357"
201	76429	76429	314.99	4549.8	0.4550	7.092264	48.050665	7° 5' 32.152"	48° 3' 2.395"
202	76445	76445	359.81	4711.8	0.4712	6.724043	48.043516	6° 43' 26.556"	48° 2' 36.658"
203	76839	76839	162.99	1255.7	0.1256	6.626447	48.037087	6° 37' 35.209"	48° 2' 13.513"
204	77043	77043	366.82	5796.1	0.5796	6.713402	48.037348	6° 42' 48.249"	48° 2' 14.453"
205	77091	77091	168.14	1350.0	0.1350	6.715717	48.037613	6° 42' 56.582"	48° 2' 15.406"
206	77113	77113	1375.30	39462.9	3.9463	7.090971	48.046868	7° 5' 27.494"	48° 2' 48.723"
207	77429	77429	224.29	2418.5	0.2419	6.712583	48.036340	6° 42' 45.300"	48° 2' 10.823"
208	77505	77505	211.92	2085.1	0.2085	6.629977	48.033491	6° 37' 47.917"	48° 2' 0.566"
209	77571	77571	632.38	13184.9	1.3185	7.088228	48.042689	7° 5' 17.621"	48° 2' 33.679"
210	77587	77587	172.80	1295.6	0.1296	6.716405	48.037092	6° 42' 59.056"	48° 2' 13.532"
211	77836	77836	360.00	7200.0	0.7200	6.703131	48.030983	6° 42' 11.271"	48° 1' 51.539"
212	77911	77911	311.90	4424.3	0.4424	6.705636	48.030626	6° 42' 20.290"	48° 1' 50.255"
213	77965	77965	858.34	19206.7	1.9207	7.085436	48.040173	7° 5' 7.569"	48° 2' 24.624"
214	77974	77974	224.29	2418.5	0.2419	6.708790	48.030025	6° 42' 31.645"	48° 1' 48.089"
215	78022	78022	180.00	1800.0	0.1800	7.085566	48.038163	7° 5' 8.039"	48° 2' 17.388"



216	78098	78098	219.55	2033.8	0.2034	7.084501	48.037653	7° 5' 4.202"	48° 2' 15.551"
217	78195	78195	376.47	6022.5	0.6023	6.874183	48.028792	6° 52' 27.061"	48° 1' 43.652"
218	78471	78471	361.30	4965.9	0.4966	6.871796	48.029329	6° 52' 18.466"	48° 1' 45.585"
219	78553	78553	1145.74	48137.7	4.8138	6.867195	48.030042	6° 52' 1.902"	48° 1' 48.152"
220	78944	78944	335.31	5994.1	0.5994	6.876629	48.027674	6° 52' 35.865"	48° 1' 39.627"
221	79182	79182	1125.30	59875.2	3.3453	6.409031	48.017559	6° 24' 32.511"	48° 1' 3.212"
222	79200	79200	538.76	9668.9	0.9669	6.879022	48.026555	6° 52' 44.478"	48° 1' 35.599"
223	79729	79729	218.93	2467.5	0.2468	6.830954	48.020969	6° 49' 51.434"	48° 1' 15.487"
224	80060	80060	232.80	2195.7	0.2196	6.832337	48.018405	6° 49' 56.413"	48° 1' 6.259"
225	80135	80135	300.00	4500.0	0.4500	6.831154	48.017957	6° 49' 52.154"	48° 1' 4.646"
226	80269	80269	367.54	5611.9	0.5612	6.832784	48.017249	6° 49' 58.024"	48° 1' 2.098"
227	80462	80462	493.93	10697.1	1.0697	6.832227	48.016283	6° 49' 56.017"	48° 0' 58.620"
228	80504	80504	170.21	1214.7	0.1215	6.831521	48.015411	6° 49' 53.476"	48° 0' 55.480"
229	81342	81342	466.54	13245.5	1.3245	6.598190	48.005240	6° 35' 53.485"	48° 0' 18.865"
230	81629	81629	384.24	7545.9	0.7546	6.513222	48.001015	6° 30' 47.599"	48° 0' 3.655"
231	81715	81715	2942.12	172326.8	3.6673	6.679848	48.004844	6° 40' 47.452"	48° 0' 17.439"
232	81762	81762	245.30	3308.5	0.3308	6.601119	48.001926	6° 36' 4.029"	48° 0' 6.932"
233	81871	81871	169.76	1228.8	0.1229	6.456407	47.997861	6° 27' 23.065"	47° 59' 52.300"
234	82586	82586	405.02	6833.5	0.6833	6.596993	47.996275	6° 35' 49.176"	47° 59' 46.590"
235	82935	82935	483.71	10542.9	1.0543	6.597978	47.994046	6° 35' 52.721"	47° 59' 38.566"
236	83349	83349	211.92	2085.1	0.2085	6.685108	47.991903	6° 41' 6.388"	47° 59' 30.850"
237	83422	83422	608.80	17008.7	1.7009	6.657683	47.991357	6° 39' 27.658"	47° 59' 28.885"
238	83523	83523	120.00	900.0	0.0900	6.380711	47.984162	6° 22' 50.558"	47° 59' 2.983"
239	83692	83692	472.93	10273.4	1.0273	6.677225	47.989840	6° 40' 38.010"	47° 59' 23.424"
240	85133	85133	931.19	22064.8	1.5282	6.712040	47.932766	6° 42' 43.346"	47° 55' 57.959"
241	86054	86054	120.00	900.0	0.0900	6.391648	47.966594	6° 23' 29.934"	47° 57' 59.740"
242	86056	86056	321.00	4807.4	0.4807	6.398728	47.966991	6° 23' 55.420"	47° 58' 1.168"

243	86119	86119	263.03	3038.1	0.3038	6.403234	47.966478	6° 24' 11.644"	47° 57' 59.319"
244	86199	86199	209.30	2390.6	0.2391	6.392786	47.965736	6° 23' 34.031"	47° 57' 56.650"
245	86233	86233	120.00	900.0	0.0900	6.393322	47.965283	6° 23' 35.960"	47° 57' 55.018"
246	92585	92585	616.48	17300.4	1.7300	7.093626	47.934453	7° 5' 37.055"	47° 56' 4.030"
247	92626	92626	372.61	7408.7	0.7409	6.639460	47.928902	6° 38' 22.058"	47° 55' 44.047"
248	92813	92813	275.19	3381.6	0.3382	7.091395	47.931651	7° 5' 29.022"	47° 55' 53.944"
249	92847	92847	120.00	900.0	0.0900	7.090750	47.931127	7° 5' 26.699"	47° 55' 52.056"
250	93012	93012	300.00	4500.0	0.4500	7.086603	47.930302	7° 5' 11.770"	47° 55' 49.086"
251	93088	93088	221.91	2712.9	0.2713	7.089391	47.929626	7° 5' 21.806"	47° 55' 46.653"
252	93223	93223	1311.92	35292.2	3.5292	7.088526	47.929953	7° 5' 18.692"	47° 55' 47.830"
253	93291	93291	337.10	5167.5	0.5168	7.087112	47.928197	7° 5' 13.603"	47° 55' 41.511"
254	93874	93874	800.60	19383.3	1.9383	7.086103	47.925085	7° 5' 9.970"	47° 55' 30.304"
255	95141	95141	526.29	11000.6	7.5014	7.088169	47.918369	7° 5' 17.408"	47° 55' 6.127"
256	100805	100805	651.41	18439.0	1.8439	6.579443	47.864091	6° 34' 45.994"	47° 51' 50.728"
257	103531	103531	717.76	22496.0	2.2496	6.582815	47.870216	6° 34' 58.134"	47° 52' 12.777"

