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WOOD TECHNOLOGY

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GEOINFORMATICS

ESTIMATION OF THE QUANTITY OF DEAD WOOD AFTER WINDTHROW THROUGH AEREAL IMAGES IN TUSCANY, ITALY

DIPLOMA THESIS

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Guides to writing a thesis:

1. Make a review of the recent literature regarding forest windthrows in Europe, and methods for their monitoring.
2. Make literature review about how sampling techniques for forest inventories as line intersect sampling could help to get a quick estimation of the volume of the dead wood in combination with geographical information systems tools.
3. Estimation of volumes of dead wood from the field to use as a control data.
4. Apply two methods of photo-interpretation, one manually and other automatic to estimate the volume of the dead wood.
5. Analyze which photo-interpretation methodology is closer to the data from the field work (control data).
6. Give recommendations and conclusions concerning both photo-interpretation methodologies and mention the disadvantages and advantages from practical point of view.

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Declaration

I hereby declare that, this thesis entitled "*Estimation of the quantity of dead wood after windthrow through aereal images in Tuscany, Italy*" was written and completed by me. I also declare that all the sources and information used to complete the thesis are included in the list of references. I agree that the thesis could be made public in accordance with Article 47b of Act No. 111/1998 Coll., Higher Education Institutions and on Amendments and Supplements to Some Other Acts (the Higher Education Act), and in accordance with the current Directive on publishing of the final thesis.

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Abstract

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Estimation of the quantity of dead wood after windthrow through aereal images in Tuscany, Italy

Tuscany has suffered severe windstorms in the last five years, causing major damages to the forests. Quantifying the damage after these disturbances has been the main concern for authorities. The objective of this study was develop a new, cost effective methodology to estimate dead wood volumes post windthrow through remote sensing and GIS tools, testing a supervised photo-interpretation in combination with LIS and an unsupervised photo-interpretation called NCC through RGB images with 0.2 m GSD. Additionally, field-assessed were obtained as control data. The study area was conducted in the Tuscany region, where 10 areas were selected. The species affected were mostly conifers. The results obtained by the unsupervised were better than supervised, but both methods did not show statistically significant differences. The NCC method showed promising results, but mostly in big areas, where the results showed accurate volumes. On the other side, small areas are not suitable to be under NCC methods yet, due to the low accuracy obtained in the volumes in this study.

Keywords: windthrow, RGB images, photo-interpretation, line intersect sampling, dead wood, Tuscany, Italy

Abstrakt

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Odhad množství mrtvého dřeva po větrné kalamitě pomocí leteckých snímků v italském Toskánsku

V posledních pěti letech bylo Toskánsko postiženo velkými vichřicemi, které zapříčinily rozsáhlé škody v lesích. Jedním z hlavních úkolů státní správy byla kvantifikace škod způsobených vichřicí. Cílem této studie bylo vyvinout novou finančně přijatelnou metodu, která by dokázala odhadnout množství mrtvého dřeva po větrné kalamitě pomocí prostředků dálkového průzkumu Země a geografického informačního systému. Byly testovány metody řízené fotointerpretace v kombinaci s liniovým výběrem (line intersect sampling – LIS) a neřízené fotointerpretace spojené s metodou normalizované křížové korelace (normalized cross-correlation – NCC) na ortofotosnímcích s vysokým rozlišením. Výsledky byly porovnávány s kontrolními daty získanými pozemním měřením. Na 10 vybraných územích severovýchodního Toskánska byla provedena oblastní studie. Zasaženy byly hlavně jehličnaté porosty. Výsledky dosažené neřízenou metodou byly lepší, avšak mezi metodami nebyly zjištěny statisticky významné rozdíly. Automatickou metodu lze uplatnit především na velkých plochách, kde jsou výsledky v porovnání s kontrolními daty velmi přesné. Naproti tomu tato metoda zatím není vhodná pro malé plochy.

Klíčová slova: škody větrem, RGB obrazy, foto-interpretace, line intersect sampling, mrtvé dřevo, Toskánsko, Itálie

List of abbreviations

ALS	Airborne Laser Scanning
ARSIA	Agenzia Regionale per lo Sviluppo e l'Innovazione nel settore Agricolo e Forestale[1]
CV	Coefficient of variation
CWD	Coarse Woody debris
DBH	Diameter at breast height
DHM	Digital Height Model
DSM	Digital Surface Model
DTM	Digital Terrain Model
EFI	European Forest Institute
FAS	Fixed Area Sampling
GIS	Geographic Information System
GNSS	Global Navigation Satellite System
GSD	Ground Sample Distance
INFC	Inventario nazionale delle foreste e dei serbatoi forestali di carbonio[2]
INS	Inertial Navigation System
IUCN	International Union for Conservation of Nature
LIDAR	Light Detection and Ranging
LIS	Line Intersect Sampling
META	Monitoraggio Estensivo dei boschi della Toscana a fini fitosanitari[3]
MR	Multiple regression

[1] Regional Agency for Development and Innovation in Agriculture and Forestry sector
[2] National inventory of forests and forest carbon sinks
[3] Extensive monitoring of forests of Tuscany for plant protection

MRI	Magnetic Resonance Images
NCC	Normalized Cross-Correlation
NFI	National Forest Inventory
NWFP	Non-wood forest products
PET	Positron Emission Tomography
PTS	Point Transect Sampling
REDD	Reducing emissions from deforestation and forest degradation
RF	Random forest
RS	Remote Sensing
SVM	Support vector machines
TLS	Terrestrial Laser System
TL	Total Length

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1. INTRODUCTION

Italy has 9,979,000 ha of forest according to FAO (2005a), ranks 54th in terms of forest surface in the world and sixth within the European Union (EUROSTAT, 2011). Tuscany is Italy's most forested region (it has more than 50% of its territory covered with forest), with a surface of approximately 1,150,000 ha (Lisa et al. 2014). Due to the enormus forest cover, Tuscany gets tremendous attention from local authorities to better manage this special natural resource. Thus, from the year 2000, the Region of Tuscany started a specific project called META[4], where the main target of the project is to define and quantify annually the forests areas damaged by insects, pests, pathogens or abiotic adversity. META will become a good monitoring tool in case the windstorms recurs in the next years. This has become more necessary considering the recent windstorm occurrences in the last 5 years. Historically, the Tuscany region has suffered permanent damage to their forests, either by fires or by diseases. In 2009, the number of fires increased by 20% over the previous year. The percentage increase was mainly in areas ≤ 1 ha (about 73.5%), in the periods of July (25.5%) and August (22.4%). A whopping 64% of the fires were caused by man (Regione Toscana, 2009). The Tuscany region has its fair share of pathogen and insects infestations. *Heterobasidion abietinum*, *Armillaria sp*. and *Lymantria dispar* infest important genus such as *Abies sp*., *Fagus sp*., *Pinus sp*., *Castanea sp*. and *Quercus sp*.

Disturbances are always a threat to the forests because they exert strong control over the species composition and structure of forests (Frelich, 2002). It is important to note that, most the European tree species have either evolved or adapted to past natural disturbance regimes (Bengtsson et al. 2000). This has been either with human intervention or just by nature. One of the most common disturbances is windthrow. Windthrow is a disturbance by wind, varies spatially and temporally in forests, from large-scale catastrophic disturbances operating at the landscape level to small-scale perturbations operating at the scale of individual trees (Ulanova, 2000). Today, this topic has become an important issue in the Tuscany region, due to the damages caused in recent years during 2013 and 2015 (LaMMA, 2015). Apart from being an unusual occurrence in the Tuscany forests, it is in general an uncommon event in Mediterranean

[4] Extensive monitoring of forests of Tuscany for plant protection

areas as described by Gardiner et al. (2010). During the recent period, authors such as Chirici et al. (2016), Pirotti et al. (2016), Bottalico et al. (2016) and Foderi et al. (2016), threw more light on the Tuscany windthrow event that happened on March 5, 2015. They described the state of the forests after the damage by quantifying the volumes of dead wood. They gave some guidelines for the forest restoration and gave an estimation of the cost of the harvest operations to extract the resulting dead wood cause by the windthrow. On the other hand, windthrows are quite common in Central Europe as well as Boreal forests. The Northern Hemispheric mid-latitude cyclones destroyed huge areas of forests in France, Switzerland, Germany and Finland (Usbeck et al. 2009a). In Finland, for example, two wind episodes in 1978 and 1982 caused the loss of about three million cubic meters of timber in both cases (Peltola and Kellomäki, 1993). On the other hand, in Switzerland, the damage caused by storm Vivian in 1990, which was then considered the storm of the century in Switzerland, was exceeded by more than 250% during the storm Lothar in 1999 (Dobbertin, 2002), reaching a wind speed of 45 m s^{-1} (Schütz et al. 2006). Several scientific works try to explain the damage patterns, mainly analyzing the structure of the forest, relief, and the wind speed, but storms of this magnitude are highly chaotic and their effects are therefore largely unpredictable (Schütz et al. 2006). The situation is that windstorms have increased in recent years and especially in Switzerland, where the storm damage was 17 times greater during the period 1958-2007 than during the period 1908-1957 and 22 times greater than in the period 1858-1907 (Usbeck et al. 2009b). The factors that could possibly explain this increase of windstorms are the growing stock, warm winter temperature and high precipitation (Usbeck et al. 2009b).

Historically, methods for the sampling and estimation of the volume in dead wood were by taking measurements in the field. This method was called line intersect sampling and is described by several authors like De Vries (1986), Kangas and Maltamo (2006), and Gregoire and Valentine (2007). This method takes into account (that is counts the number of intersections) intersections of the sample lines with line features in the landscape (Kleinn, 2007). The downside of this method is that, it is expensive and time-consuming (Pirotti et al. 2016). Therefore, in cases where measurements demand frequent repeats, finding faster and cheaper methods of estimating dead wood volume will be more prudent. In the future, there will be the need to find solutions that will be cost effective, transmit information much quicker. Furthermore, coming out with new technologies that can merge remote sensing techniques with conventional ground sampling methods will become a powerful tool for quantifying windstorm damages in the future.

Main objectives of the thesis are:

- Develop a cost effective method to estimate volume of dead wood post windthrow through fieldwork and remote sensing tools

- Comparison between estimates of a simple supervised photo-interpretation in combination with line intersect sampling and unsupervised photo-interpretation method called kernel normalized cross-correlation against values of ground truth

2. THEORETICAL FRAMEWORK

2.1 Description and characterization of forests in Italy

According to FAO (2015), Italy has a territory of 29,414,000 ha, of which 9,297,000 ha are covered with forests; representing 31.6% of the country surface. Other wooded land occupies 1,813,000 hectares (6.2%). Three geomorphological types: Alps, Apennines, and Islands categorizes the main distribution of forests in Italy. The region with the biggest area of forest in Italy is Tuscany, with 1,015,728 ha, followed by Piemont and Lombardy, with 870,594 and 606,045 ha respectively. The regions with the lowest forest area are Puglia, Molise and Valle d'Aosta. The forest characterized by ownership in Italy is 66.2% private property, 33.4% public property and 0.3% area not classified by the feature of the property (INFC, 2005).

Table 1. Forest and another wooded land by the administrative region in Italy (INFC, 2005)

District territorial	**Forest area (ha)**	**Other wooded lands (ha)**	**Total forest area (ha)**	**Land area (ha)**
Piemonte	870,594	69,522	940,116	2,539,983
Valle d'Aosta	98,439	7,489	105,928	326,322
Lombardia	606,045	59,657	665,703	2,386,285

Alto Adige	336,689	35,485	372,174	739,997
Trentino	375,402	32,129	407,531	620,690
Veneto	397,889	48,967	446,856	1,839,122
Friuli V.G	323,832	33,392	357,224	785,648
Liguria	339,107	36,027	375,134	542,024
Emilia Romagna	563,263	45,555	608,818	2,212,309
Toscana	1,015,728	135,811	1,151,539	2,299,018
Umbria	371,574	18,681	390,255	845,604
Marche	291,394	16,682	308,076	969,406
Lazio	543,884	61,974	605,859	1,720,768
Abruzzo	391,492	47,099	438,590	1,079,512
Molise	132,562	16,079	148,641	443,765
Campania	384,395	60,879	445,274	1,359,025
Puglia	145,889	33,151	179,040	1,936,580
Basilicata	263,098	93,329	356,426	999,461
Calabria	468,151	144,781	612,931	1,508,055
Sicilia	256,303	81,868	338,171	2,570,282
Sardegna	583,472	629,778	1,213,250	2,408,989
National total	**8,759,200**	**1,708,333**	**10,467,533**	**30,132,845**

The Italian forest is mostly composed of broadleaved (4,913,918 ha) and conifer forests (1,261,057 ha). Mixed forests accounts for 1,030,334 ha. Moors and heathland, sclerophyllous vegetation and transitional woodland/shrub accounts for the rest forest land area (FAO, 2005b). The most important tree species in Italy taking into account quantity, basal area and volume are European beech (*Fagus sylvatica*), Norway spruce (*Picea abies*) and Sweet chestnut (*Castanea sativa*). According to the last national forest inventory in Italy made by INFC in 2005 (the data from 2015 is still in construction), Italy has an average of 1,364 trees/ha, a basal area of 20.4 m^2/ha, a volume of 144.9 m^3/ha and a current increment of 4.1 m^3/ha.

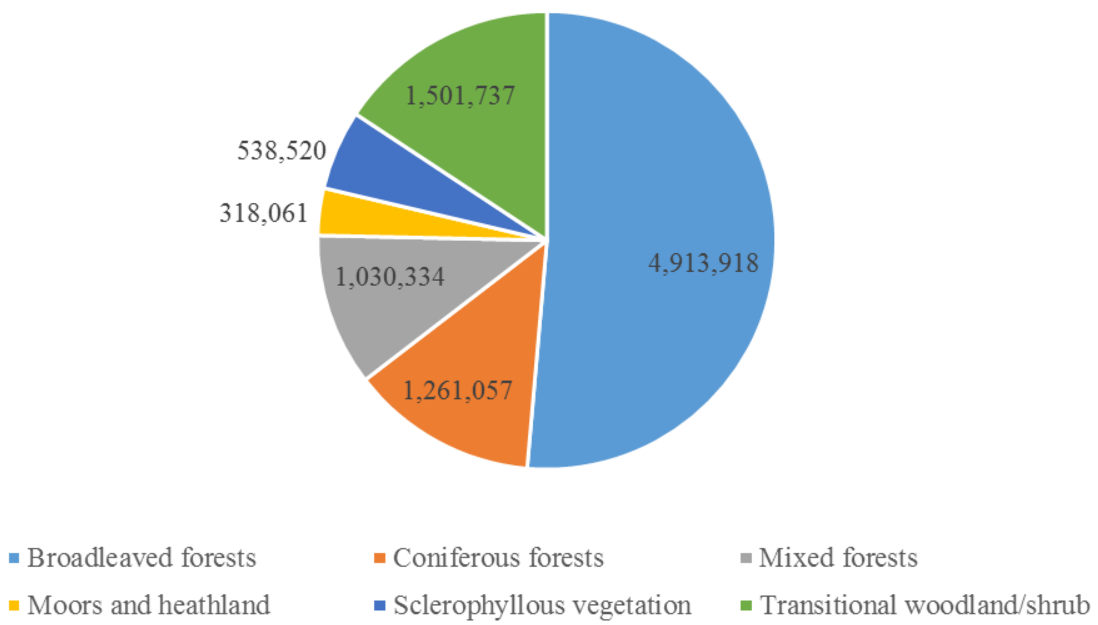

Figure 1. Area of national classes (FAO, 2005b)

There are 17 forest type classifications in Italy. The most dominant are mainly composed of broadleaved forests. Temperate oaks forests (*Q. petraea*, *Q. pubescens*, *Q. robur*) is the biggest forest type in Italy, with 1,084,247 ha, followed by Beech forests (*F. sylvatica*) with 1,035,103 ha and Mediterranean oaks forests (*Q. cerris*, *Q. fraineto*, other species) with 1,010,986 ha. Moreover, the conifer forests are mainly composed of the following; Norway spruce forests (*P. abies*) (586,082 ha), Larch and stone pine forests (*L. decidua*, *P. cembra*) (382,372 ha) and Black pines (*P. nigra*, *P. laricio*, *P. leucodermis*) (236,467 ha).

Additionally, there is some artificial forests with artificial poplar plantation of about 66,269 ha mainly located in the regions of Lombardy and Piemont. The total area of plantations of others deciduous forests is 40,958 ha mainly found in Sardegna, (representing 45.1% of the total). With 7,066 ha of the total 14,998 ha of conifer plantations in Italy found in the region of Sardegna, it has largest conifer plantation in Italy (INFC, 2005).

High forest and coppice are the main silvicultural systems practiced in Italy. High forests constitutes 42% and the remaining 58% belong to coppice (Bottalico et al. 2014). Coppice forests are located along the lower slopes of the Alps and all along the Apennine range from the coast to the upper mountain zone (Ciancio et al. 2006), whiles high forests are located in better sites, identified mainly by conifer plantations. Protected areas in Italy reach approximately 19% of the total area of the country. However, in terms of the forest area, strictly protected areas according to the standards of the International Union for conservation of Nature (IUCN) is estimated at a 11% and are in the form of national parks, integrate natural reserves, biogenetic reserves and oases (Corona et al. 2004). There are 23 national parks, 152 regional parks and approximately 200 regional reserves.

2.2 Tuscany Forests

The Tuscany region has an area of 2,299,018 ha with nine provinces and a Metropolitan city. Its regional capital is Florence. The physical geography comprises 66.5% hills, 25.1% mountains and 8.4% of plain areas. The Tuscany region has a Mediterranean climate. As per the data provided by Regione Toscana (2008), the region records a mean temperature of 13.9°C and in terms of precipitation shows a positive average value of 155 mm, with a maximum of 1,843 mm in the station of Cutigliano (Pistoia) and a minimum of -360 mm in the station of Cortona (Arezzo). Forests represent the 50.1% of the regional territory, with 1,086,016 ha. The Tuscany region has the largest forest cover in Italy. However, it occupies the third place in coefficient of woodiness, after Liguria and Trentino Alto Adige, with 47%. With respect to coefficient of woodiness, the national average for Italy is approximately 29% (INFC, 2005). Furthermore, is important to mention that almost 10% (227,000 ha) of the region's forested area is protected. There are 3 national parks, 3 regional parks, 2 provincial parks, 36 state nature reserves, 37 provincial nature reserves and 52 protected areas of local interest. The ownership of the forests in the Tuscany region belong principally (80%) to the private sector, 13.8% to the public sector, while the ownership of remaining 6.2% is a non-classified type of property (Regione Toscana, 2009).

Regarding the data presented about necromass during the year 2009[5] by the National Forest Inventory and carbon sinks, Tuscany is the region in Italy with the largest volume of necromass, with 8,603,633 m^3 of dead trees standing, 1,590,694 m^3 of necromass on the ground and 1,369,105 m^3 by residual stumps. In total, it reaches

[5] Data from May 2009 and available in new derived information by the National Forest Inventory and carbon sinks

11,563,432 m^3, concentrating 15% of the necromass distributed in the national territory (Regione Toscana, 2009). The necromass trend is likely to increase in the Tuscany region due to recent windstorms in 2013 and 2015.

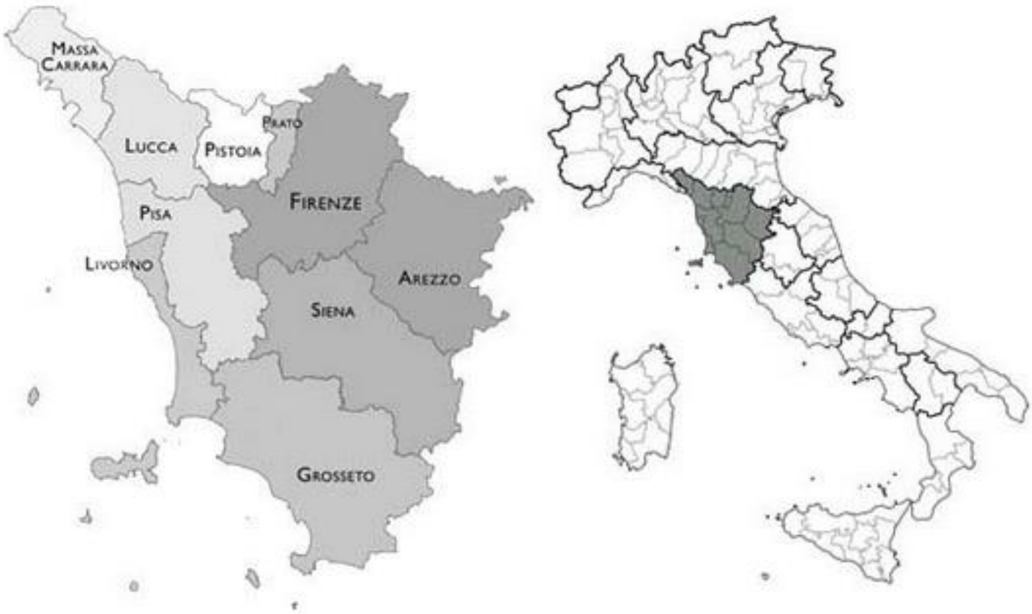

Figure 2. Tuscany region and their provinces

The province with the biggest amount of forest is Grosseto, followed by Florence and Arezzo. While, the least forested regions are Prato, Lucca, and Pistoia. However, the highest coefficient of woodiness can be found in the provinces with the greatest extensions of mountainous territory that is in Lucca and Massa-Carrara. While the provinces with the lowest coefficient of woodiness are located in Pisa and Grosseto, marked by a strong agricultural influence (Regione Toscana, 2013).

Table 2. Forest area (ha) distributed by the 10 provinces in the Tuscany Region (Regione Toscana, 2008)

Province	**Area (ha)**
Grosseto	186,672
Florence	174,320
Arezzo	169,920
Siena	156,704
Pisa	107,776
Livorno	85,952
Massa-Carrara	77,520
Pistoia	54,368
Lucca	52,640
Prato	20,144
Total	**1,086,016**

The species composition in the Tuscany region is mostly deciduous broadleaved (79%), evergreen broadleaved (13%) and conifers (8%). The most important deciduous broadleaved species are Turkey oak (*Quercus cerris*), Chestnut (*Castanea sativa*) and Pubescent oak (*Quercus pubescens*). About evergreen broadleaved, the species with more presence are Holm oak (*Quercus ilex*) and Cork oak (*Quercus suber*). On the other hand, conifers species have poor representation. The most common conifer species are Maritime pine (*Pinus pinaster*), Black pine (*Pinus nigra*) and Larch (*Larix decidua*) (Regione Toscana, 2008) (figure 3). Most of conifer forests in Tuscany originated from reforestation projects.

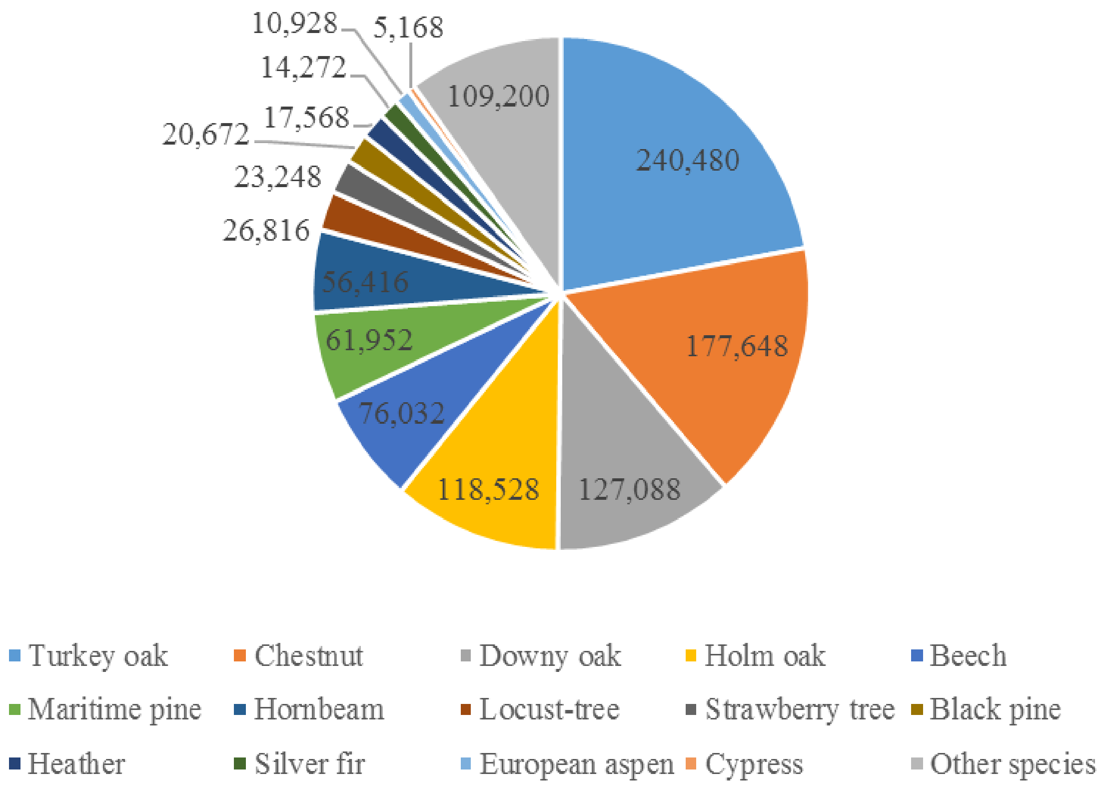

Figure 3. Distribution of the main tree species by area (ha) in the Tuscany region (Regione toscana, 2000)

The forest of the Tuscany region has three functional divisions. They are as follows: conservation (139.168 ha), protection (95,584 ha) and production (851,264 ha). The main difference between conservation and protection is that conservation belong to forest located in areas upper than 1,500 m a.s.l. and with forests of high conservation value; and protection focuses on forests with a coverage of less than 40%, with high slope, reduced fertility and presence of bedrock. On the other hand, the production function focuses on the traditional or conventional forest management to produce timber (Regione Toscana, 2013). The Tuscany inventory considers other vegetation types such as Mediterranean maquis, shrubberies, chestnut trees and scrubland as non-wood forest products (NWFP). They are non-wood forest products (NWFP) because the products got from them (e.g. ornamental trees, nuts, blueberries, honey etc.) are not timber/wood based.

Table 3. Forest area (ha) distributed by the inventory categories according to the forest inventory of the Tuscany region (Regione Toscana, 2000)

Inventory categories	**Area (ha)**
Forest	735,184
Area in renovations	112,320
Mediterranean maquis	110,432
Shrubberies	57,568
Chestnut trees	32,336
Riparian formations	17,392
Brush	6,528
Scrubland	5,696
Garrigue of Mediterranean environment	4,240
Transiently areas without vegetation	4,240
Areas damaged by pollution	80
Totale	**1,086,016**

Forest fires due to climatic conditions is a prime issue in the region. Amongst the Mediterranean countries in Europe, Italy is second in the mean surface by fires with 11.9 ha, only surpassed by Greece with 34.8 ha[6] (Tuscany reached 2.2 ha). In 2008, the Tuscany region recorded 2,564 forest fires. The most affected provinces were Pisa (664), Lucca (449) and Grosseto (301) subdivided into forest fires, brushwood fires and crops fires (Regione Toscana, 2008). Aside forest fires, pathogen and insect infestation in the Tuscany region is of great concern as well ARSIA[7] (2009). Important genus such as *Abies sp.*, *Fagus sp.*, *Pinus sp.*, *Castanea sp.*, *Quercus sp*. and *Cupressus sp*. have suffered phytosanitary damage. Species with several damages are *Abies alba*, affected by *Heterobasidion abietinum* and *Armillaria sp.*, *Fagus sylvatica* by *Biscogniauxia nummularia*, *Pinus nigra* by *Diplodia pinea*, *Castanea sativa* by *Dryocosmus kuriphilus*, *Quercus sp.* by *Thaumetopoea processionea*, *Lymantria dispar*, *Euproctis chrysorrhoea* and *Biscogniauxia mediterranea*; and *Cupressus sempervirens* by *Seridium cardinale*. The region considers this a paramount concern and as a result there have to date constant monitoring and research.

[6] Comparison between national data and those of the other Mediterranean countries calculated for the period 2004-2008
[7] Agenzia Regionale per lo Sviluppo e l'Innovazione nel settore Agricolo e Forestale

2.3 Damages by windthrow in the European and Italian forests

Disturbances are a major factor influencing the species composition of ecosystems – wind is no exception (Agren and Andersson, 2012). Windthrow is associated with exceptionally strong winds generated locally by thunderstorm downbursts or by extensive intense low-pressure systems is often termed catastrophic (Gardiner et al. 2008). The problem caused by the windstorms are several, such as a high economic impact, changes in the forest planning and potential problems with insects, fungus, and fires after the collapse of the trees. This is mainly due to the woody material remaining on the ground after the windthrow causing an ideal situation for the arrival of insects and fungus in the necromass. An example is the distribution of *Heterobasidion* and *Armillaria* root rots in Vallombrosa on *Abies alba* (Benedek, 2016). In the case of the forest fires, the accumulation of logs on the ground after the windthrow creates a high volume of combustible material hence generating a high risk, especially during the summer in countries such as in Spain, France, Italy, Portugal, and Greece. According to the European Commission in (2010), during 2009 the fires recorded in these five countries mentioned above, affected a total area of 323,896 ha which is almost double the total area affected in 2008. Therefore, non-extraction of dead wood could generate a series of negative impacts, such as the loss of wood to supply sawmills and all the environmental woes that forest fires cause. The damage windthrow causes is dependent on several factors. Some of these factors are namely: tree height, stem taper, stand density, tree species and soil type (Talkkari et al. 2000). A study made by Ulanova 2000, identified that older trees have higher levels of damage than younger trees. Also, identified that the most severe damage occurs in Aspen (*Populus tremula*), Spruce (*Picea abies*) and Birch (*Betula spp.*) in boreal forests condition.

In Europe, windthrow has a very high impact on forests. Windthrow damages constitutes 51% of all recorded damages followed by wildfires (16%) and snow (4%) (Gardiner et al. 2013). With more than 130 storms, causing significant damages Europe's forests over the last 60 years; it is without a doubt that, Central Europe is probably the most affected by this phenomenon (Don et al. 2012). According to the Swiss National Forest Inventory (NFI), two-thirds of all unplanned felling in

Switzerland are due to windthrow (Thürig et al. 2005). A proof of this was the windstorm “Lothar” and “Martin” in 1999 that hit large parts of western and central Europe. France was the worst affected country with 176 mil m^3 followed by Germany with 34 mil m^3 and Switzerland with 14 mil m^3 (Gardiner et al. 2010). In Switzerland, windthrow losses reached 12.7 mil m^3 of timber. The loss equals 2.8 times the annual national timber harvest (Meyer et al. 2008). On the other hand, in the French Alps, windthrow accounts for roughly 25% of annual wood harvested and the damage caused by the Lothar and Martin storms reached as much as 10% of the total standing volume in France (Ancelin et al. 2004). In Austria, post-windthrow wood harvest fluctuated between approximately 1 and 10 mil m^3 of timber annually 1990 – 2012 that corresponds to shares of 4 to 50% of the annual cut (Pasztor et al. 2015). Another windstorm that caused serious damages in Europe was Kyrill in 2007. This windstorm caused losses of 54 mil m^3 of timber wood mainly in the central part of Europe. The most heavily hit countries were Germany with 28 mil m^3, the Czech Republic with 12 mil m^3 and Austria with 2.25 mil m^3 (Gardiner et al. 2010).

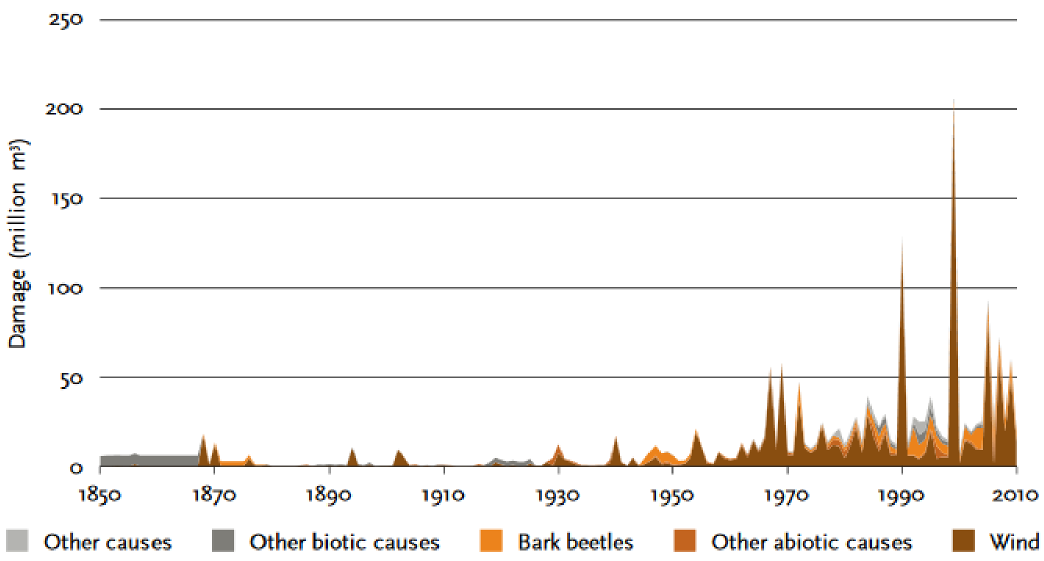

Figure 4. Total damage occurring in European forests (mil m^3) due to different disturbances (Gardiner et al. 2013)

Windthrow damages in Swedish forests increased during the last century reaching a peak in the 1980s. Nilsson et al. (2004) reported a loss of 110.7 mil m^3, destroyed by 77 recorded windstorms, with the severe storms in 1954 and 1969 accounting the 49% of the total damage. Most recently, Sweden suffered a windstorm called Gudrun in 2005, with very high economic impact. As an example, the average prices of sawlogs of Spruce and Pine in Southern and Central Sweden was only 63% and 86%, respectively, of those in the year before the storm (Gardiner et al. 2010). In Finland, the most destructive wind damage occurred in November 2001, when two storms blew down 7.3 mil m^3 of timber in southern and western parts of the country (Peltola et al. 2010). However, in the past years, there have been in a decline in forest stand quality in Finland (up to 1.1 million). This was mainly due to disturbances such as the wind, snow, and frost. The area corresponds about 5.6% of the country's forest reserves (Peltola et al. 1999). Denmark is has also had its share of windthrow damages. In November 1981, the country suffered one of the most severe windthrows in their history. In one night, approximately 2.8 mil m^3 of timber came down due to a storm (Wichmann and Ravn, 2001).

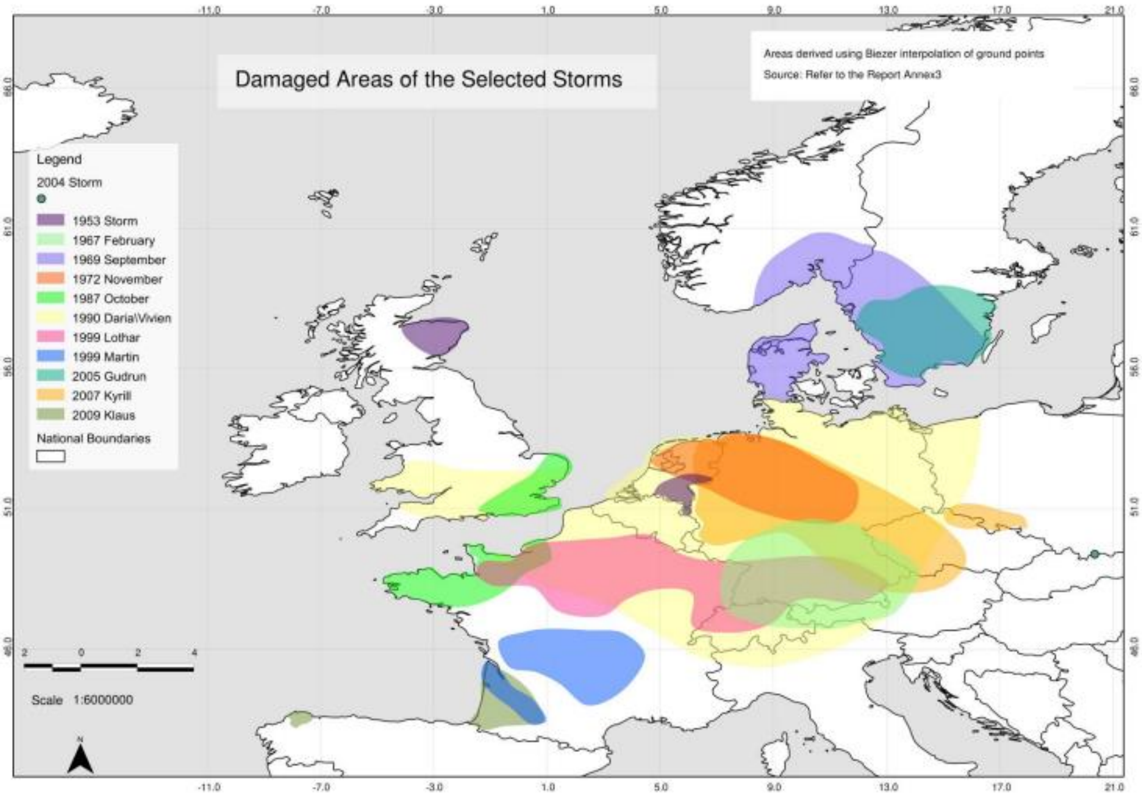

Figure 5. Estimated areas affected by selected storms in Europe (Gardiner et al. 2010)

According to the reports submitted by the European Forest Institute (EFI), the damages by windthrow in the Mediterranean forests are minimum. In the case of Italy, during the year (2000), the FAO published the area of forest affected by disturbances and Italy obtained 136,000 hectares damaged, distributed in 33.8% by fires, 48.5% by insects and

17.6% by others disturbances (including windthrow). Therefore, the impact of this type of disturbance is very low in Italy compared to other countries in the central and north part of Europe. In 2013 and 2015, two major windstorms hit the region of Tuscany (Bottalico et al. 2016). On March 5, 2015, a gust of wind slammed the Tuscany region, causing the fall of trees, power outages, and serious structural damage. The highest speed was in 2015 in Passo Foce al Giovi (province of Lucca) with a speed of 188 km/h (LaMMA, 2015), while in the year 2013, the highest speed recorded was 130 km/h in the mountains areas in the town of Passo del Giogo (LaMMA, 2013).

2.4 Line intersect sampling applied on areas damaged by windthrow

The Line Intersect Sampling (LIS) was a technique successfully applied by Warren and Olsen (1964) in measuring the volume of post-logging residue above a certain size limit in *Pinus radiata* plantations in New Zeland (Van Wagner, 1968). This technique is used to estimate the volume of pulpwood that is left after clearfelling operations. The measurements the LIS generates are economically acceptable in an operational scale for the sale of pulpwood with a reduced waste pieces measurement frequency as compared to the conventional means of plot sampling (Warren and Olsen, 1964) as well as 55% time compared to conventional cruising methods (Bailey, 1970). The underlining principle of LIS is counting intersections of the sample lines with line features in the landscape, which obviously depends on to the length of the sample line in the landscape (Kleinn, 2007). A particle of CWD (coarse woody debris) is selected into the sample if its projection onto angle is intersected by a transect (Affleck et al. 2005). This means that, the sample line called “transect” is the plot design, which defines how to select the circular cross section from the wood pieces lying on the ground that are included in order to obtain an observation. The method only requires a diameter measurement at the point of intersection to estimate the volume directly in cubic meters of coarse woody debris per unit area (Böhl and Brändli, 2007). Lastly, the line transect shape and length depend on the sampling protocol. The length is a very important feature in the design of sampling because the time of measuring per line increases with longer lines (Marshall et al. 2000). This intuitively gives greater preference for few long transects as compared to numerous small ones (Mandallaz, 2008). However, in order to optimize time in the field work dealing with the line intersect, the following three things needs to be minimized: 1) the amount of walking apart from actual sampling 2) the amount measured distance in addition to the actual sample lines and 3) the number of starting points to be located (Van Wagner, 1982).

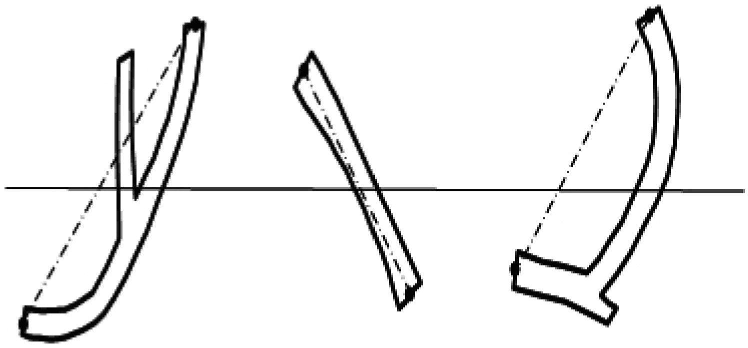

Figure 6. With the Line Intersect Sampling method, a "needle" defines selected sample objects. Only the intersections of the sample line with this needle leads to the selection of the object (Kleinn, 2007).

At a single sampling location, we can locate two or more plots of different sizes or transects with multiple segments that are very much used with elements of similar shapes that tend to be oriented in the same direction, as for example a populations of trees blown down by a hurricane or felled by a logger (Gregoire and Valentine, 2007). Affleck et al. (2005), adopted the term "radial transect", referring to transect consisting of one or more segments directed outwards from a common vertex. The radial transect can be considered in different shapes such as straight-line, L-shaped, + -shaped line, or Y-shaped transects. On the other hand, the polygonal transects are made up of three or more segments forming a closed figure, such as a triangle, square, and more complicated polygonal shapes. In a radial design, the sampling location, is in the vertex of the transect whiles the polygonal transect has its starting point in the first segment. The orientation of the first segment may be selected uniformly at random or fixed in advance of sampling (Gregoire and Valentine, 2007).

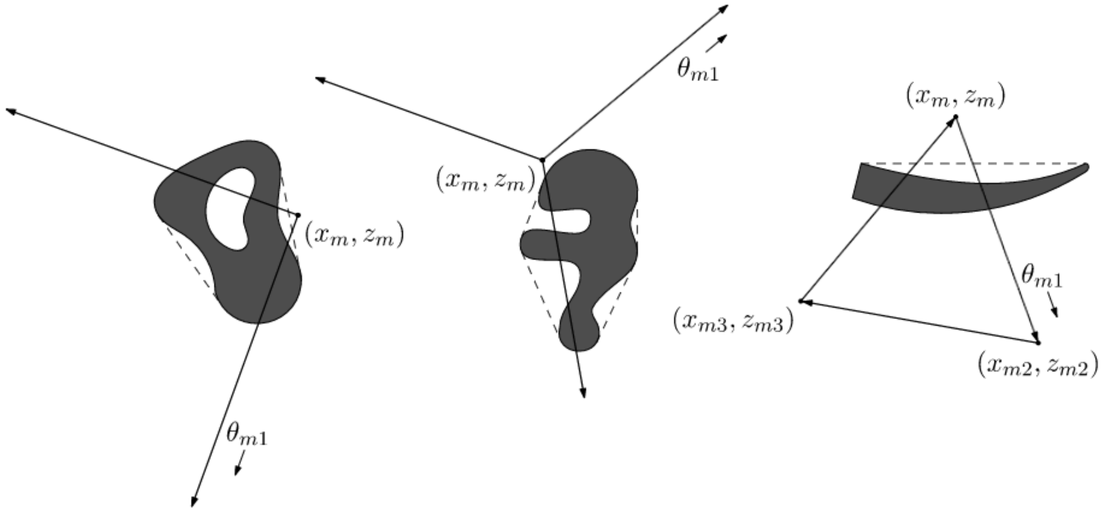

Figure 7. Examples of transects with multiple segments (Affleck et al. 2005)

The localization and orientation of the transect lines can be randomly or systematically, as the length and shape of the samples lines. This will depend on the sampling protocol but according to Kaiser (1983), the transect line should be randomly placed on the area of interest. The random transect is identified by the angle of the line through the origin perpendicular to it and by the distance between the origin and the transect (Mandallaz, 2008). However, Kleinn (2007) described the buffon's needle problem. This seeks to see if transect of length is thrown randomly on an area completely covered by equidistant parallel lines with a certain distance finding the probability that transect intersects with one of the parallels. This problem is quite relevant in the localization and orientation of transects in the sampling design. Principally because if the transects go in the same direction to where the trees have fallen, the probability that transects will intersect the trees it is unlikely. This is because if the transects go parallel to the directions of the trees, it is very probable that the number of the observations will be very low. Probably, the application of transects consisting of one or more segment used two transects joining perpendicularly in an ell shape as a way to sample elements more robustly (Gregoire and Valentine, 2007).

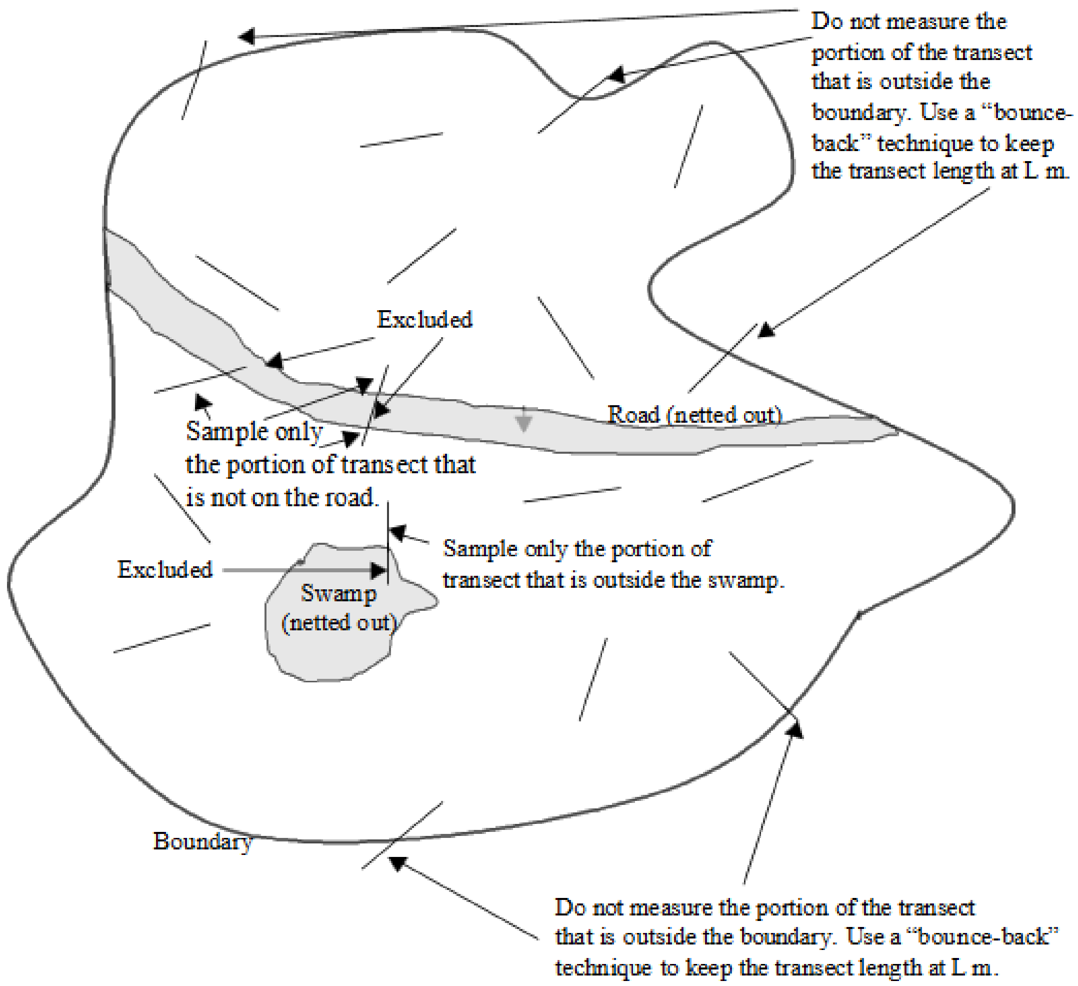

Figure 8. A hypothetical random layout of line transects on an area of interest (Marshall et al. 2000).

Other issues regarding the size, shape, and orientation of transects are the edge effects. In some cases, some transects are at the edges of the interest area. This is where a part of transect is located outside the sample, this happens normally as for example in the cluster sampling, based on a grid of square units. Some authors like Gregoire and Monkevich (1994) and Affleck et al. (2006) were dealing with the edge effect in order to provide alternative solutions to this issue. There are two well-known methods called walkback method and reflection method. These methods can be used to design fixed-length transects as a correction for edge-effect bias. Affleck et al. (2006) demonstrated that the reflection method solves the edge problem for designs that use symmetric radial transect with fixed orientation, such as straight-line or X-shaped transects. However, this method is not applicable for polygonal transects.

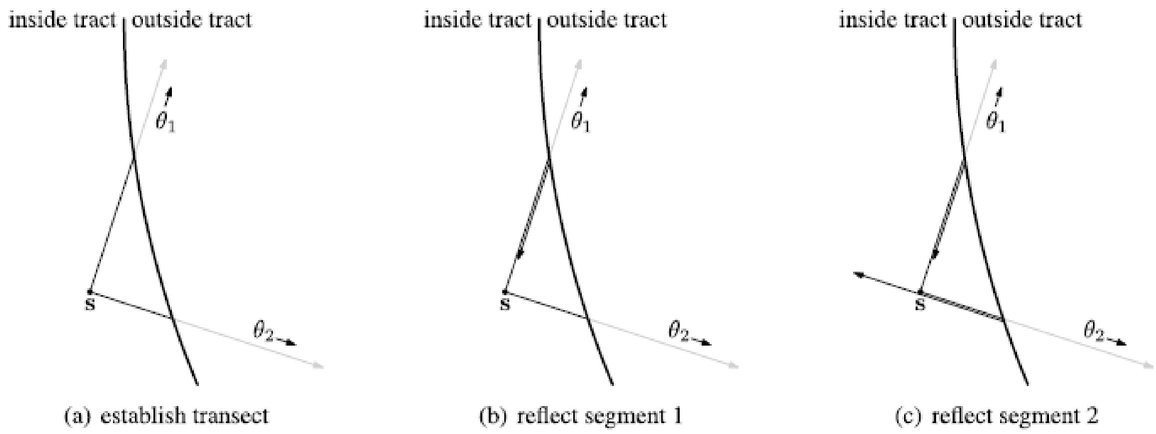

Figure 9. Implementation of the reflection method for an L-shaped; the portion of each segment overlapping the boundary is reflected back into the track toward the sample point (Affleck et al. 2006).

According to Van Wagner (1968), the formula of line intersects sampling shows an unbiased estimate of the wood volume if the following assumptions are completed. The assumptions are: (1) the pieces are cylindrical, (2) all pieces are horizontal and (3) the pieces are randomly oriented. However, if the assumptions proposed by Van Wagner are not completed, LIS does not necessarily produce unbiased estimates, but the error of these estimates becomes difficult to estimate analytically (Bell et al. 1996).

If computation of tree volume is by using Huber's formulas[8], the equation to estimate the volume with LIS will be:

$$\hat{T} = \frac{\pi^2}{8L}\sum_{i=1}^{m} d_i^2 \quad (1)$$

Where *V* is volume per unit area

d is piece diameter at intersection

L is length of sample line

From variation between the lines, the variance of the LIS estimator can be calculated (De Vries, 1974).

[8] Formula used to calculate the volume of a log, using only the measuring of the diameter at the middle of the log.

$$Var(\hat{T}) = \frac{\sum_{j=1}^{n} L_j \left(\hat{T}_j - T_j \right)^2}{(n-1)\sum_{j=1}^{n} L_j} \quad (2)$$

Where n is the number of lines

$\hat{T}_j$ is the total volume per hectare estimated from line j

$\hat{T}$ is the total volume per hectare in the area

L_j is the length of line j

In the formula of the variance in LIS, there is an assumption that the lines measurements are in random directions, or that the trees have fallen in random directions. Without these assumptions held, the formula may give inefficient estimates (Kangas and Maltamo, 2006).

The precision of the sampling depends on the size of the plot and the variability of the material. To a get a more reliable standard error, the sample size should not be less than 10 lines. Preferably, 20 lines will suffice. (Van Wagner, 1982).

$$S_{\bar{x}} = \frac{s}{\sqrt{n}} \quad (3)$$

Where $S_{\bar{x}}$ is standard error in units of volume per unit area

n is number of sections in the total sample

s is standard deviation

Due to the importance to quantify the volume of the dead wood, many authors such as Warren and Olsen, (1964); Van Wagner, (1968) and Kaiser, (1983) have worked in the perfection of methods that can improve the estimation of these volumes. Line Intersect Sampling (LIS) is a well-known method. It has proven to be very efficient in comparison with plot-based methods. The objects to be sampled can be, for example, logs, roads, streams, hedges or projections of tree crowns (Ringvall and Ståhl, 1999), even it can be used in quantification of forest edges, in order to understand and mitigate the effects of forest fragmentation on biodiversity (Esseen et al. 2006). Different fields can employ this technique. However, greater use has been on quantifying wood waste. For example, Bailey (1970) proposed a simplified method of sampling logging residue. This method sought to verify the adequacy of LIS for assessing logging residue on both tractor-logged and cable-logged area. In addition, the work done by Warren and Olsen, (1964) originally focused on the measuring logging residue in an extensive clear-cut area of plantation-grown *Pinus radiata* stands. Nevertheless, nowadays this method has taken great relevance to estimating volume of dead wood after disturbances like windthrow. Many authors like Priewasser et al. (2013) and Waldron et al. (2013) have applied LIS to assess the impact that this phenomenon has caused in the forests. It has been the concern worldwide that some countries have included an assessment of dead wood (or necromass) volume in the National Forest Inventory (NFI), such as in Switzerland (Böhl and Brändli, 2007) France (Teissier du Cros and Lopez, 2009) and Italy (INFC, 2005).

2.5 Remote sensing tools to the assessment of damages by windthrow

Remote sensing is a means of obtaining physical data of an object without touch or contact (Campbell and Wynne, 2011). The following are examples of remote sensing devices through which we obtain data: cameras, optical-mechanical scanners, linear and area arrays, lasers radar systems, sonar, seismographs, gravimeters, magnetometers, and scintillation counters (Jensen, 2007). Currently, remote sensing techniques are applied in combination with other modern geospatial technologies such as geographic information system (GIS), global navigation satellite system (GNSS), mobile mapping and Google Earth (Weng, 2012). In the practice, remote sensing involves collecting information through different devices of a particular object or area e.g. magnetic resonance images (MRI), positron emission tomography (PET), X-rays and space probes. According to Weng (2010), an image representing the scene under observation, normally gives the output of a remote sensing system. The next step is the analysis and interpretation of the image through GIS tools in order to extract useful information from the image. The thematic information can be about soil, vegetation, water depth, and land cover as well as metric information such as area, volume, slope angle etc. The difference between this two types of information is that with the thematic information, it can be obtained through visual interpretation of remote sensing images or computer-based digital image analysis, while, metric information is extracted by using the principles of photogrammetry.

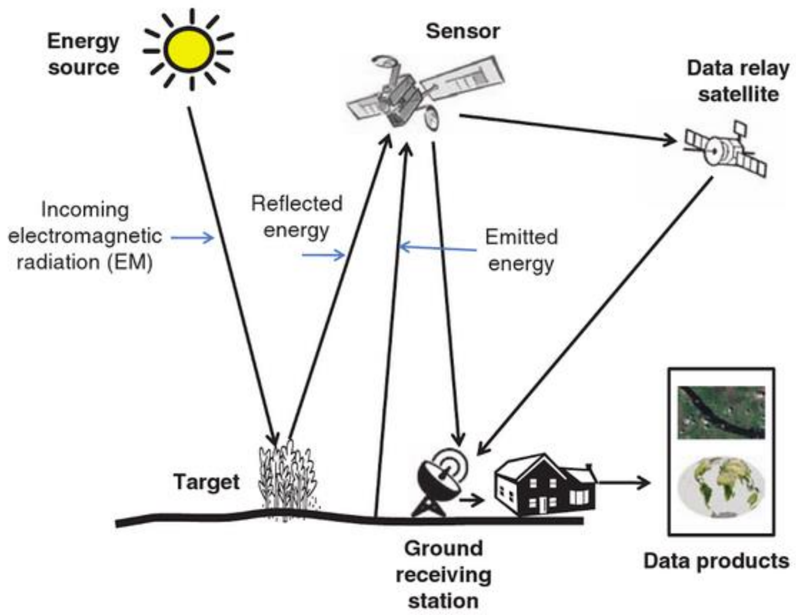

Figure 10. An illustration of a remote sensing process (Weng, 2012)

The advances in remote sensing in the field of forestry have been on the increase in recent years and have become part of the forest surveys. Generally, an important role of remote sensing is forest mapping. Remote sensing also helps in estimating timber volume and biomass assessment in particular. In the case of timber volume, there are several works dealing with this topic, especially for their use in the forest planning to the state and private forestry companies. A study carried out by Naesset (1997) indicated it is possible to use laser scanner data to obtain estimates of forest stands volumes with an accuracy likened to that of the inventory method based on aerial photo-interpretation. Nevertheless, for this type of methodology requires careful stratification which needs to be in line with the provided forest types. Biomass is another variable of great interest. On one side, biomass can be used for dendroenergetic projects (a potential source of heating houses and cooking food), where the estimation of biomass is crucial in the market to sell it and on the other hand, allow an estimation of the carbon content present in forest ecosystems. In this context, LiDAR will play a prominent role in biomass estimations, due to the expected technical innovations and the performance of LiDAR data for biomass assessment (Koch, 2010). The quantification of biomass will be of great relevance in themes such as carbon fixation and climate change. This is why projects such as REDD+[9] presents a good platform to develop new methodologies through remote sensing techniques when it comes to the estimation of biomass in forests. However, it is important to note that, for both, such as timber volume and biomass estimation, ground truth will always be necessary as described by Naesset (1997). In order to control the data obtained from the remote sensing tools and compare it with the data obtained from the fieldwork, some calibration plots will be of essence.

As described above, variables such as volume and biomass have always been a goal for researches related to remote sensing. Although techniques of measuring variables mentioned above have tremendously developed with time, it sure have not been without challenges, which keep appearing over time. A clear example of this is the volume estimation of dead wood. The quantification of dead wood is of importance not only from the economic perspective but also ecological (that is with respect to nutrient cycling and species habitation). Considering, the high cost that the conventional measuring techniques come with, remote sensing is now receiving more attention than ever before. Some authors, such as Pesonen et al. (2008), Pirotti et al. (2016), and Chirici et al. (2016) applied new methodologies in order to get information on CWD volumes in a short time and with a low cost after windthrow through RGB images and airborne laser scanning (ALS). Clearly, investigations related to RGB images and ALS have yielded good results even with windthrow problem areas. However, ground truth data remains very credible and accurate. More so because in many cases the data from ALS produces an overestimation of the values.

The technology of ALS performs a laser scanning from an aerial platform, the laser can be located in a plane, helicopter or through of a non-piloted airlift, mostly referred to as drone. This technology is composed of GNSS receptors, inertial navigation system (INS), units of emission and reception laser. A typical laser scanner comprises laser ranging units, opto-mechanical scanner, control and processor units (all of which form the main units) (Wehr and Lohr, 1999). Several products can obtained by ALS, as digital terrain model (DTM), digital surface model (DSM), digital height model (DHM), maps and biometric estimates.

[9] Reducing emissions from deforestation and forest degradation

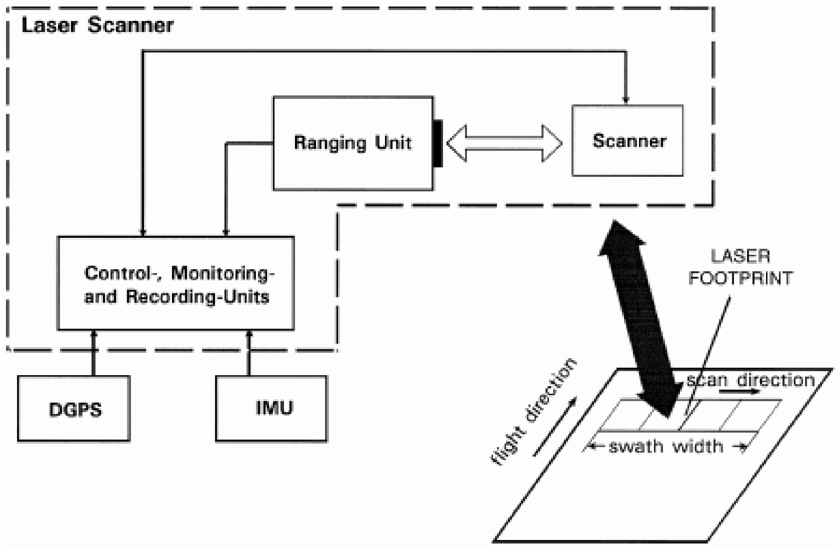

Figure 11. A typical Airborne Laser Scanning system (Wehr and Lohr, 1999)

Nevertheless, from the practical point of view, the products generated by ALS could be very useful in forest operations. This is evident from Foderi et al. (2016) who described how to optimize the timber harvesting in order to provide an economical sustainability of wood extraction through a correct estimate volume as a first step. In addition, ALS can be a powerful tool in forest planning. This is also evident from Bottalico et al. (2016) who proposes restoration methods for future management and ALS can be useful in monitoring how the forest is recovering through estimates of volumes and biomass over the time.

3. MATERIALS AND METHODS

3.1 Description of the area of study

The study was conducted in the northeastern part of Tuscany region, in central Italy (figure 12). Tuscany is the region with the largest area of forests in Italy, with 50.1% of its total surface covered with forest. The forest cover in the region is composed mainly of deciduous broadleaves (79%), evergreen broadleaved (13%) and conifers (8%) (Regione Toscana, 2008). The region has a Mediterranean climate but parts close to the coast get some continental attributes from the plains and valleys within the inner Tuscany.

Between the late evening of 4th (18 UTC) and the morning (06 UTC) of 5th March 2015, strong winds hit the region of Tuscany (Pirotti et al. 2016), reaching a speed of 188 km/h. The origin of the dominant direction was from northeast (LaMMA, 2015). This caused extensive damage in urban and forest areas, mainly in pure even aged stands of uniform structures (Bottalico et al. 2016). The species most affected were conifers mainly Maritime pine (*Pinus pinaster*) and Black pine (*Pinus nigra*) (Chirici et al. in press). A coverage of photos was used in order to estimate volumes of the dead wood based on RGB images with very high spatial resolution (pixel size = 20 cm). Ten (10) out of the total 1,354 plots was selected based on parameters such as quality of image, percentage of darkness and amount of crowns. Consideration was solely given to images a manual photo interpretation could be taken. After identifying the suitable images for the supervised photo-interpretation, we selected the 10 areas for measurement.

From the 4th to 8th of May 2015, a carrier plane with rotating blades took images. Attached to the carrier plane (Eurocopter AS350 B3) was a LiDAR RIEGL LMS-Q680i sensor and a system of digital cameras DIGICAM H39 RGB and CIR optical instrument (Chirici et al. in press)[10]. Due to the high economic cost of this type of flights, it was not possible to cover the entire area of the region (1,015,728 ha). However, we conducted a preliminary phase to identify the main areas that needed monitoring according to the local forest authorities. This was amounted to a total area of 43,623 ha. The carrier plane (Eurocopter AS350 B3) flew at a height of 1,100 m above terrain level and with an average speed of 70 km/h.

[10] Despite the presence of ALS data in our materials, the supervised and unsupervised photo-interpretation was carried out only with RGB images with high resolution

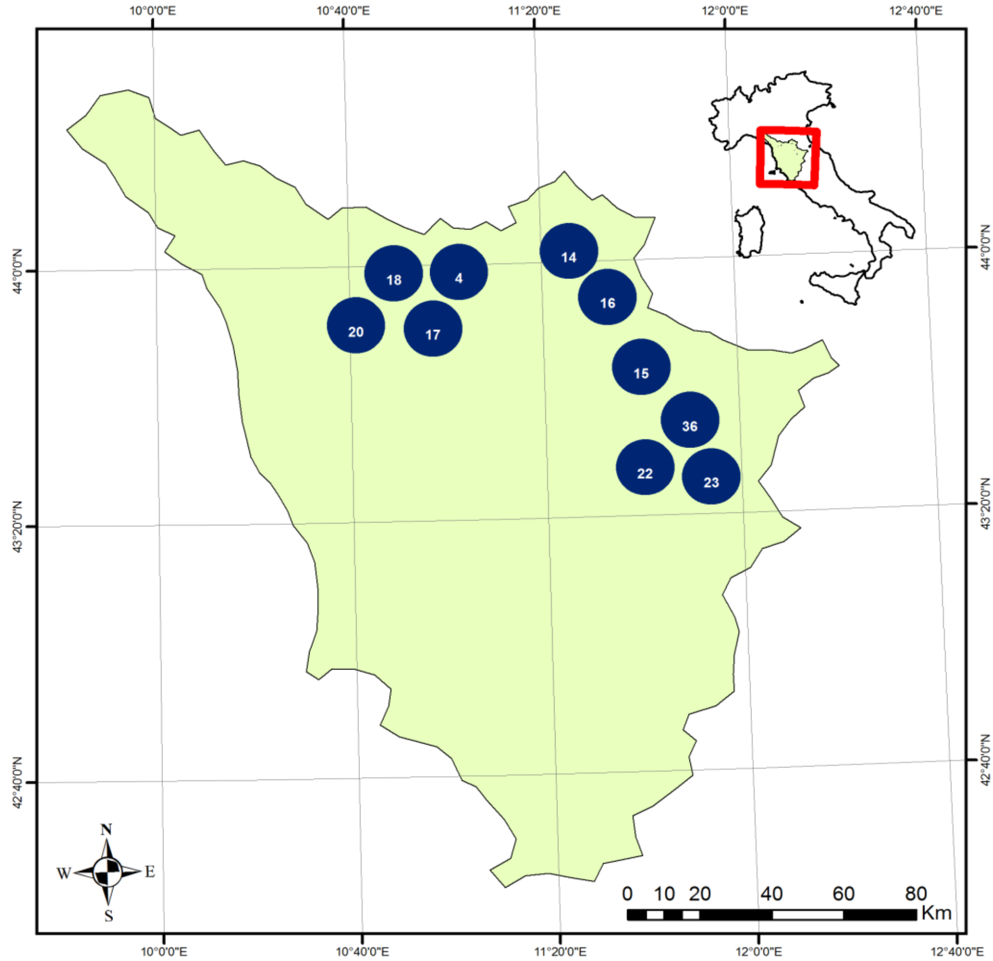

Figure 12. Area of the study with the 10 plots selected in the north east of Tuscany, Italy

The plots selected belong to the provinces of Pistoia, Florence, Lucca and Arezzo, where the area principally affected by the windstorms was artificial monoculture plantations of conifers and the main tree species were Black pine (*Pinus nigra*), Silver fir (*Abies alba*) and Douglas fir (*Pseudotsuga menziesii*). The range of the surfaces varied from 1.1 to 25.9 ha though from the total area of each stand, not all of it suffered damage by the windstorms. Table 4 gives the effective area of damage. The range of the effective damage varied between 0.5 (Borgo San Lorenzo) to 20.7 (Lucca) ha. The DBH (diameter at breast height) varied between 22.0 (Marliana) and 57.0 (Castiglion Fibocchi) cm. Moreover, the range of the mean total volume is quite broad. This is because it relates to the surface of the plots, which ranges from 123.7 to 14,641.6 m^3.

Table 4. The 10 plots selected to be measured with their main attributes

ID	Province	Specie	Area (ha)	Min DBH	Max DBH	Damage (ha)
4	PISTOIA	Pinus nigra	4.2	45.0	51.0	3.3
14	FLORENCE	Pinus nigra	2.8	37.0	43.0	0.9
15	FLORENCE	Abies alba	8.4	45.0	51.0	5.0
16	FLORENCE	Pinus nigra	1.5	37.0	43.0	0.5
17	PISTOIA	Pinus nigra	3.5	22.0	28.0	3.2
18	PISTOIA	Pinus nigra	1.9	37.0	45.0	1.2
20	LUCCA	Pinus nigra	25.9	45.0	51.0	20.7
22	AREZZO	Pinus nigra	1.8	44.0	50.0	1.2
23	AREZZO	Pinus nigra	1.9	51.0	57.0	1.4
36	AREZZO	Pseudotsuga menziesii	1.1	41.0	47.0	0.6

3.2 Calibration plot

As a first stage, we measured the variables, DBH and TL (total length) in one sample line with GIS tools. The same variables (DBH and TL) were later measured in the same sample line in the field. This was help authenticate the GIS measurements to vouch for its suitability before proceeding with the supervised photo-interpretation. We used an orthophoto with a very high spatial resolution with a pixel size was 20 cm. A sample line of 100 m of random direction was tested using the ArcMap 10.1 software by applying the tool "*measure*" where 38 trees intersected the sample line making it possible to measure the DBH and TL. After that, with the help of the GNSS, we identified 10 trees measured with GIS tools on the field (figure 13). The instruments used in the field were the caliper for DBH and the digital laser distance meter (Rangefinder) measuring tape for total length (TL). We made a comparison between data obtained through fieldwork and supervised photo-interpretation. As per our comparison, we encountered some problems with ID 3 and 7. The tree ID 3 was outside the sample line and the top of the crown of tree ID 7 was impossible to identify because it was overlapping with crowns of nearby trees. To avoid generating incorrect data on these trees, measurements for ID 3 and 7 did not take place at all.

Table 5. Comparison data between RGB images and fieldwork

	Orthophoto		Fieldwork		Difference	
ID	**DBH (cm)**	**TL (m)**	**DBH (cm)**	**TL (m)**	**DBH (cm)**	**TL (m)**
1	38.0	29.0	41.0	27.0	-3.0	2.0
2	37.0	20.0	32.0	20.5	5.0	-0.5
3	0*	0*	44.0	20.0	0*	0*
4	37.0	31.0	46.0	31.7	-9.0	-0.7
5	35.0	32.0	41.0	28.5	-6.0	3.5
6	33.0	33.0	41.5	25.0	-8.5	8.0
7	42.0	0**	48.0	0**	-6.0	0**
8	34.0	27.0	36.0	26.0	-2.0	1.0
9	45.0	26.0	52.0	32.4	-7.0	-6.4
10	40.0	27.0	39.0	26.5	1.0	0.5

*Tree measured was outside the line sample

**It was not possible to identify the top of the crown

The table 5 shows the DBH (cm) and TL (m) differences amongst the ten trees measured and comparison with the measurement done in the orthophoto as well as in the fieldwork. After statistically analyses by paired t-test, there were no significant differences in DBH, as well in the TL (in the case of DBH the p-value was quite borderline). Since the DBH was in centimeters and the TL in meters, the result of the analyses made sense, where in DBH showed higher different respect to TL, being normal due to differences in measurements scales (the variable of DBH, being on a small scale (cm) becomes more sensitive when measuring with GIS tools). Hence, it is possible to measure both variables from an orthophoto with GIS tools. However, considering the time spent, it is practically time consuming measuring both variables. The time consuming constraint is evident when measuring for instance the total length of the trees. This is because it is quite difficult identifying the crown tops be it in orthophoto as well as field measurements. Actually, it took us almost 2 hours to measure the ten trees even with three operators present. It is also important to mention that the sample line was very close to the main road, optimizing the time taken to locate the sampling line. Acknowledging the time demands of measuring the two variables, the diameter was the only variable used in the formula for estimating dead wood through LIS. Other authors included the length of the tree as a variable in the formula (Husch et al. 1972, De Vries, 1973). However, it is rare to use two variables to estimate volume with dead wood due to the time demands. In any case, the outcome of either one or two variables does not vary significantly. For this reason, we chose to use the diameter as the only variable for the volume estimation.

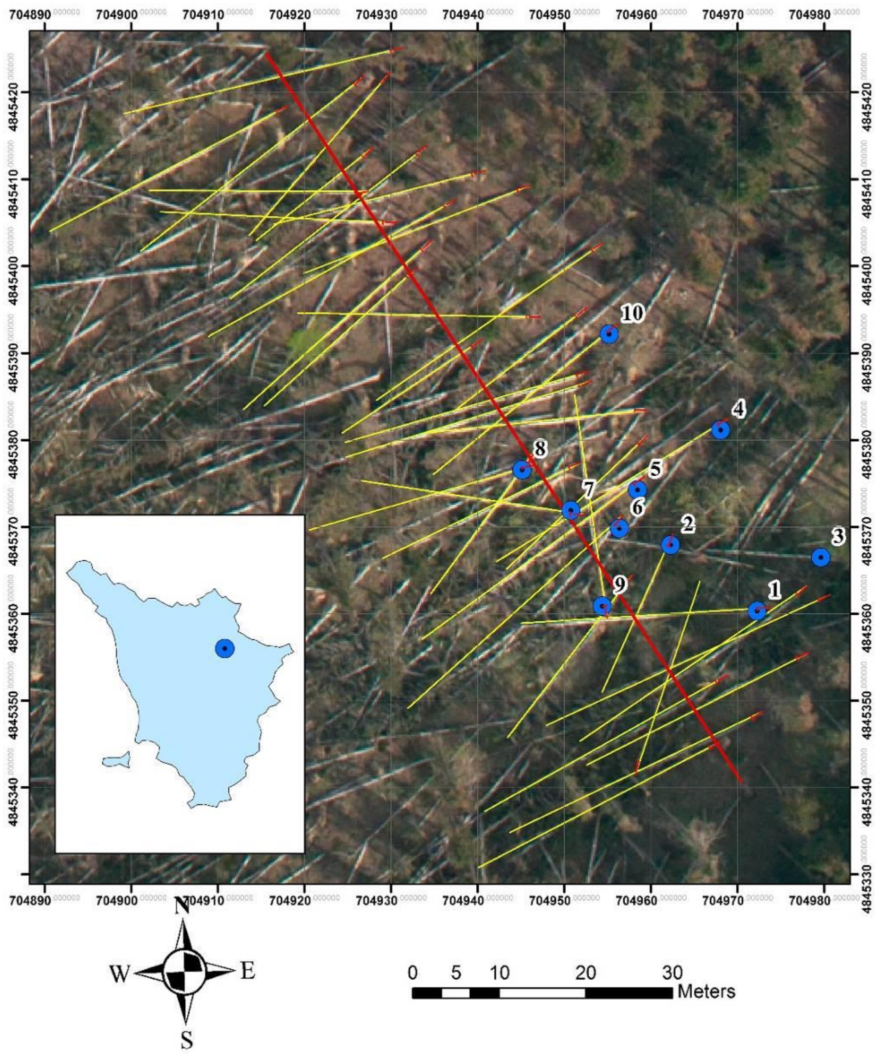

Figure 13. Sample line of 100 m length used to calibrate information from the RGB images and field data

3.3 Length and number of transects

The steps below defined the methodology used to determine the total length and the total number of transects per hectare according to the surface of the polygon.

1) Selection of a pilot area of 1.9 ha located in Vallombrosa forests, close to Florence (figure 14).

2) Transect with different lengths ranging between 90 and 880 m/ha were tested in the selected pilot area.

3) The monte-carlo method estimated the variance and relative standard error.
The number of repetitions in the simulation was 10,000 times. These results were used to determinate the optimal length (m/ha) of transect.

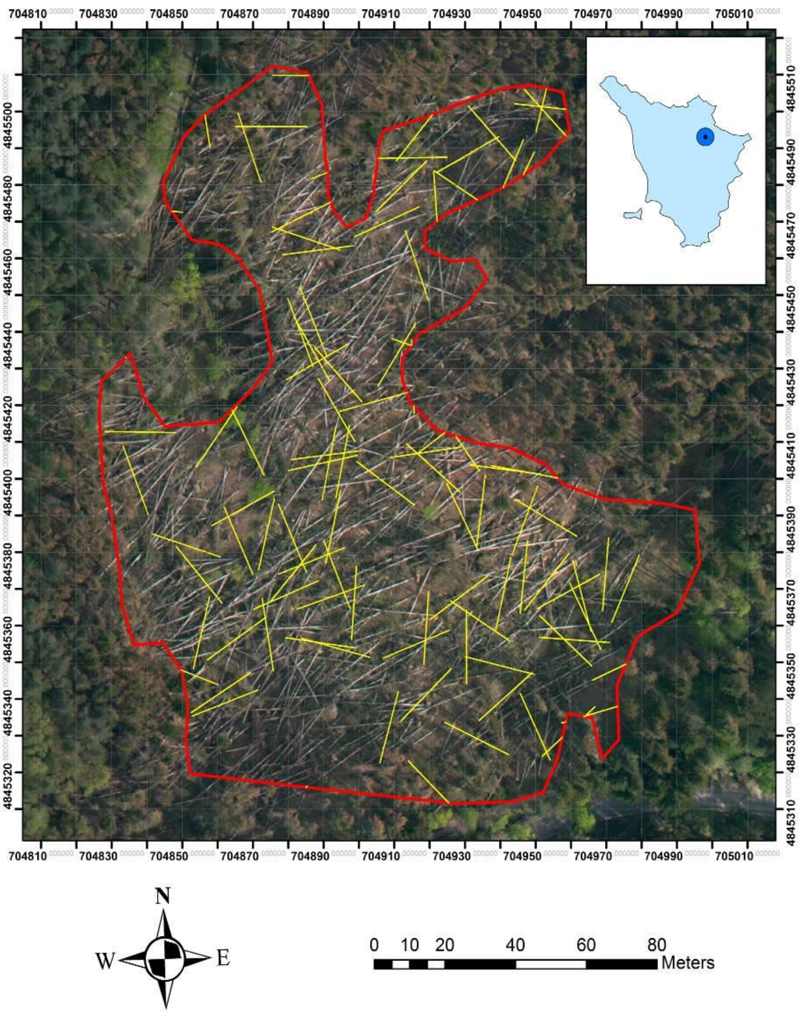

Figure 14. Pilot area used to determinate the number of the transects

The results of the Monte Carlo simulation (Figure 15) shown clearly that the curve became constant approximately to the 500 m/ha. We decided to use transects of 20 m. In order to determine the total number of transect per each plot, the area (ha) must be multiplied by 500 then divided by 20. In this way, it is possible to define the number of transects according to the area of the plot. On the other hand, the reason for implementing transects of 20 m was mainly in order to avoid the edge problem. According to the literature, it is much more practical to use longer sample lines (Mandallaz, 2008) but it increases the risk of encountering edge problems, particularly in very narrow parts of the plot. It complicates the implementation of long sampling lines. A good example is the area 17, where the particular shape of the plot complicates the implementation of the lines (see appendix). The majority of the selected plots are with a small area, with the only exception of the area 20. The great disadvantage of working with short lines is the time needed for their location, especially when people are working on the field.

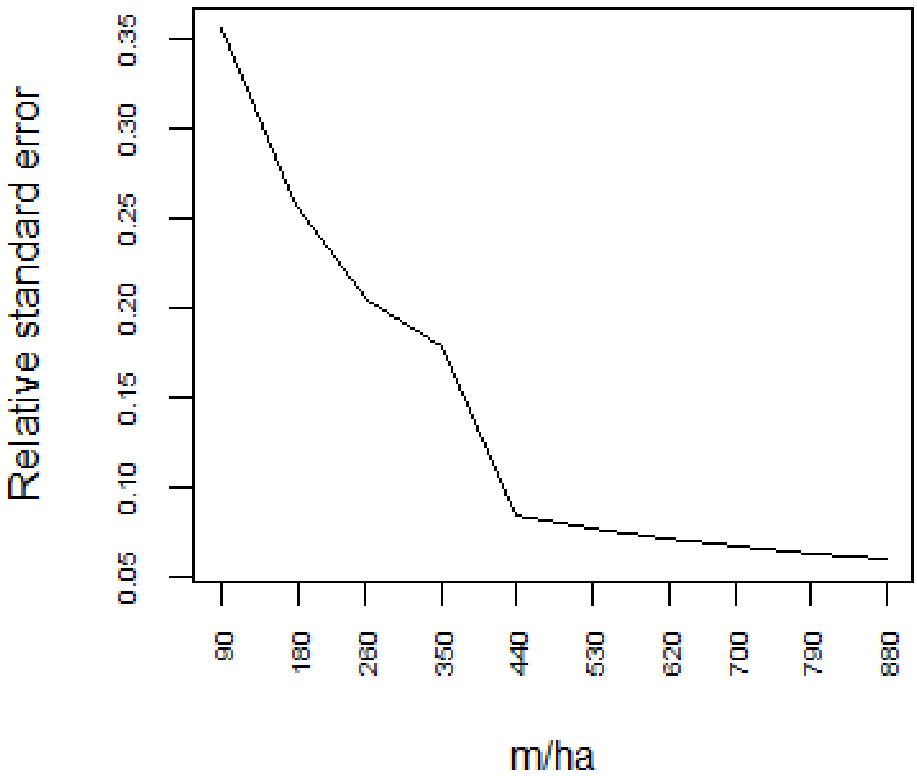

Figure 15. Monte Carlo simulation used to obtain the total length of transects per hectare (Chirici et al. in press)

The number of transects implemented in each of the study areas was quite heterogeneous, varying between 27 (area 36) to 647 (area 20) lines (table 6). This is obviously due to the fact that the number of transects is proportional to the area of the study plots. Nevertheless, with the exeption of the area 20 (as in the fieldwork and in the supervised photo-interpretation), the work can be carried out in a prudent time. However it is necessary to consider that the selected areas were relatively small hence in cases larger areas, the time used in the supervised photo-interpretation and especially in the fieldwork would not be accepable.

Table 6. Number of transects in each plot according the area

ID	Province	Specie	Area (ha)	Length (m/ha)	Length (total)	Length (20)*
4	PISTOIA	Pinus nigra	4.2	500	2113.5	106
14	FIRENZE	Pinus nigra	2.8	500	1421.0	71
15	FIRENZE	Abies alba	8.4	500	4220.0	211
16	FIRENZE	Pinus nigra	1.5	500	774.5	39
17	PISTOIA	Pinus nigra	3.5	500	1764.5	88
18	PISTOIA	Pinus nigra	1.9	500	961.0	48
20	LUCCA	Pinus nigra	25.9	500	12940.5	647
22	AREZZO	Pinus nigra	1.8	500	877.5	44
23	AREZZO	Pinus nigra	1.9	500	969.5	48
36	AREZZO	Pseudotsuga menziesii	1.1	500	545.5	27

*Number of transects 20 m length

3.4 Reflection method

As previously mentioned, one of the most recurring problems with the sampling of LIS are the problems with the edge effect. This problem occurs when a sampling line is located at the edge of the study area hence a part of the sampling line falls within the study area and the rest not. To rectify this, the Walkback and Reflection methods deal with edge effect in LIS. In our methodology, we decided on the Reflection method. With this method, the portion that extends outside of the area is folded back at the boundary atop the portion that falls within of the area (Gregoire and Valentine, 2007). We first identified all the sampling lines found in the edges, cut them and finally, the segment gotten from the sample rolled back to the original sample line (figure 16). Because of this, all logs that intersecting with sample lines and modified with the reflection method will have the value of the diameter obtained doubled when using the formula for estimating the volume.

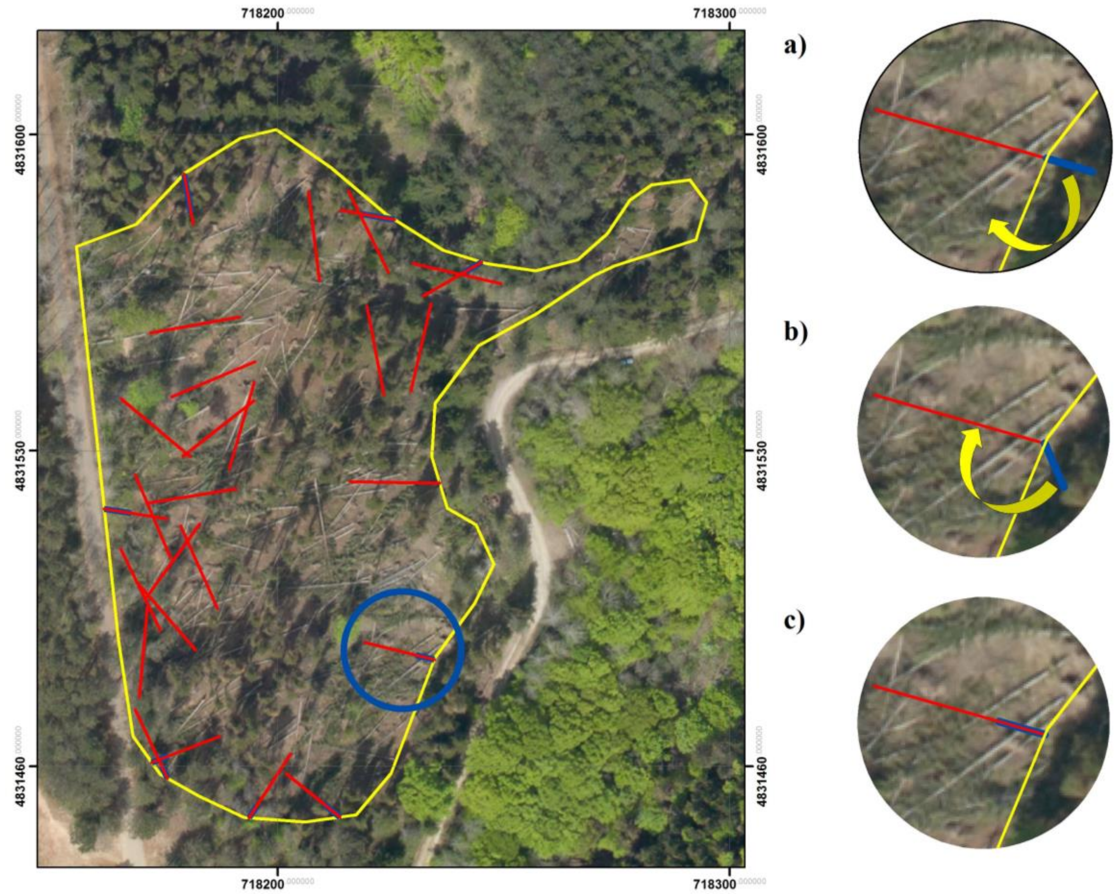

Figure 16. Example of reflection method in the area 36 in three steps

Determining the number of lines with edge effect is dependent on two main parameters thus the area and shape of the plot. The larger a plot, the less likely it is to encounter edge effect problem. In the case of plots with similar areas, the difference will be in the shape of the plot. The probability of encountering edge effect is low when plot shapes are either circular or square. On the other hand, plots with shapes that have narrow sections or sharp corners have the tendency is that the number of the lines with problems of the edge effect is high.

Table 7. Number and percentage of lines with edge effect in each area of study

ID	Area (ha)	Length (20)	Number of lines with edge effect	% of lines with edge effect
4	4.2	106	11	10.3
14	2.8	71	13	18.3
15	8.4	211	14	6.6
16	1.5	39	10	25.6
17	3.5	88	20	22.7
18	1.9	48	9	18.7
20	25.9	647	56	8.6
22	1.8	44	9	20.4
23	1.9	48	8	16.6
36	1.1	27	10	37

In our ten areas of study, it is clear that for area IDs 15 and 20 (representing the largest areas) the percentage of lines with edge effects were very low recording 6.6 and 8.6% respectively. The smallest area (36) showed the highest percentage of lines with edge effect (figure 17). The rest of the plots has similar areas and the percentage varied between 10.3 and 25.6% (table 7).

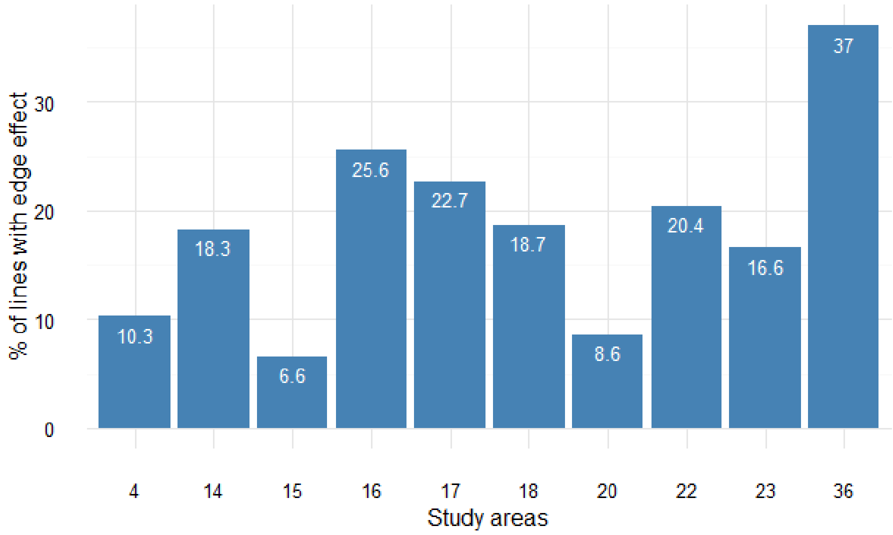

Figure 17. Histogram with the percentage of lines with edge effect in each area of study

3.5 Supervised photo-interpretation

We used the supervised photo-interpretation in combination with the LIS methodology. This entailed measuring of diameters of all the trees that intersect the sample line. Measurements were taken at the point where the sample line intersects the tree and not at the DBH point. The supervised photo-interpretation were taken with RGB (red, green, blue) orthophotos obtained on May 2015 (aerial images) based on the color model with high resolution (0.2 m ground sample distance (GSD)), polygons and transects lines in vector format as simple as lines with two vertices. According to the area affected by the windthrow, we manually created borders for the polygons. The software used was ArcMap 10.1 under student license.

Figure 18. Example of a bad line in the area 16 with 0 intersections and a good line in the area 20 with 8 intersections

Two layers were created in ArcMap. The first shapefile labelled “*lines*” and the second “*diameter*”. The first layer (lines) constituted the dispersion of sampling lines of 20 m each using a GIS tool that were randomly distributed along each plot. The number of observations was proportional to the area of interest. In the second layer, which concerns the diameter, the first step was to identify all the intersections in the segment of sampling and later, through a tool in GIS called “*measure*”, we proceeded to measure the diameter as a vector line (figure 18). After measuring the diameters of each of the intersections, we calculated the volume in m^3/ha (equation 1) taking into account the total length of transect as 20 m, π^2 and the number eight (8) as a constant as depicted in the formula described by De Vries (1973). However, because the number of intersections varied between 0 and 14, it was not possible to systematize the calculation in the excel file hence it was necessary to make the summation of each one of the lines and later estimate the volume of each single case.

Sometimes, due to the poor quality of the images, the intersections were not easily recognizable and this complicates the log measurements. In such situations of poor image quality, the logs were not measured at all. It is important to note that in the supervised photo-interpretation, especially with the presence of tree crowns, is very common to confuse a shadow with a log. Because of this, we preferred to omit some cases, which was difficult to clarify as in its recognition and for its measurement especially when the photo-interpreter is unable to identify the limits of the log clearly in order to arrive at diameter value. For this reason, the methodology duly accounted for intersections by each area of study (supervised photo-interpretation and ground truth) for later comparison.

3.6 Unsupervised photo-interpretation

The material used in the unsupervised photo-interpretation was the same used in the supervised photo-interpretation. We analyzed the RGB images with 0.2 m GSD with an adaptive template cross-correlation approach in order to detect and quantify the logs that remained on the ground after windthrow. This method entails calculating at each position of the image under examination a function that measures the degree of similarity between a template and a portion of the image (Di Stefano et al. 2004). In others words, template cross-correlation is a high-level machine vision technique, that identifies the parts on an image that match a predefined template (figure 19). The ten areas were tested by normalized cross-correlation by Pirotti et al. (2016), where a 13x13 pixel kernel were simplified as a linear-feature representation of a cylinder, applying different rotation of angles with a sequence from 0º to 170º with 10º steps (figure 20). The normalized cross-correlation (NCC) value were recorded for each pixel and for each image of all angles. The features tested were eight percentiles (75, 80, 85, 90, 95, 99, 99.9 and 1), sum of NCC values and number of pixels with NCC above 0.55. Lastly, the notion behind a template cross-correlation approach is that the trees damaged through windthrow, will have a certain directionality the moment they fall similar to lines in the image.

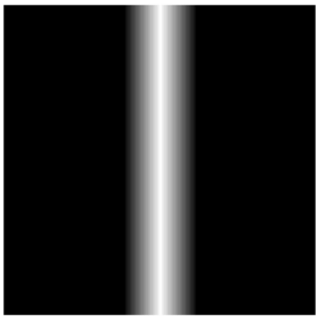

Figure 19. Example of a template at 90° in a felled tree (Pirotti et al. 2016)

In order to calculate the normalized cross-correlation, is important to define the equation (4), where *I* is the image under examination, *T* the template, of size *N* x *M* pixels and I_c (x,y) the sub image of *I* at position (x,y) having the same size as the template (Di Stefano et al. 2004). *N* and *M* are respectively the numbers of rows and columns of the kernel which for our study is 13. So, the NCC between the temple *T* and the image *I* at position is defined as:

$$NCC(x,y) = \frac{\sum_{j=1}^{N}\sum_{i=1}^{M} I(x+i, y+j) \cdot T(i,j)}{\sqrt{\sum_{j=1}^{N}\sum_{i=1}^{M} I^2(x+i, y+j)} \cdot \sqrt{\sum_{j=1}^{N}\sum_{i=1}^{M} T^2(i,j)}} \in [0,1] \tag{4}$$

The frequency distributioon of NCC values in each image is then used to predict the volume of dead wood. We assumed that areas with greater amount of woody material on the ground will provide a distribution of the NCC values to higher values in the image due their similarity with the kernel.

At the end, three models were tested in machine learning for the regression model in order to predict the volume of dead wood. Those methods were support vector machines (SVM), multiple regression (MR) and random forest (RF).

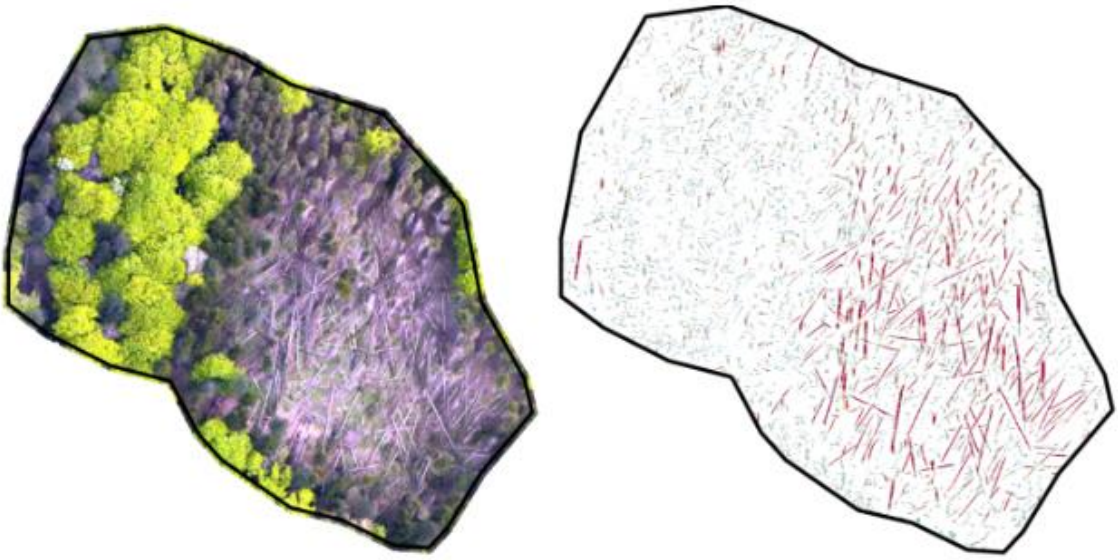

Figure 20. Application of kernel normalized cross-correlation in the area 16 (Pirotti et al. 2016)

3.7 Ground truth

The field data collection procedure followed the same protocol as applied in the supervised photo-interpretation using LIS method (Kaiser, 1983) with transect lines of 20 m. The number of the samples were determined according to Monte-Carlo simulation using the relative standard error, through different lengths ranging between 90 and 880 m/ha (see 3.3). LIS is typically applied in aerial photographs when rapid area estimations are desired (Kleinn, 2007) like in our case of study (for more details of this sampling technique see the chapter 2.4). We used calipers to collect the field data by measuring the diameter at the point where the transect line crosses the log. The operator also had the support of a GNSS to localize the position of the same samples lines that were previously measured by the supervised photo-interpretation. The importance of measuring the correct sampling lines in the field is crucial for the subsequent analysis. Usually, an approximate range of 0-28 logs can intersect a line sample. On the other hand, it is important to mention that the method applied with unsupervised photo-interpretation does not consider the number of intersections through LIS, where the system used to quantify the volume of dead wood was completely different in respect of supervised photo-interpretation and ground truth. Thus, the GIS layers, such as the "*polygons*", and the "*lines*" were the same between ground truth and supervised photo-interpretation. Students from University of Florence carried out the field data during the period of spring and summer in 2015. Ground truth was the most time consuming and labor-intensive method considering the high number of operators and the time employed in the task.

Figure 21. Collecting data in the area damaged by the windthrow in Vallombrosa forests, Tuscany region (Photo taken by Francesca Giannetti).

3.8 Statistics

The statistical analysis was carried out using the last version of the software R Studio 1.0.136 which used descriptive statistics to summarize the information from the dataset of ground truth, supervised photo-interpretation and linear regression in order to compare both photo-interpretation methods against ground truth.

3.8.1 Descriptive statistics

In our case study, we used the mean to summarize the information obtained as in the diameter and volume measurements by the supervised photo-interpretation and ground truth as a measure of the central tendency. While for dispersion, we used the standard deviation, variance and coefficient of variation. In order to compare the errors of both methodologies of photo-interpretation applied, we used a simple formula of percentage of difference, where the exact value was the ground truth and the approximate value was one of the photo-interpretation method. This formula shows how close the approximate value is to the real value (formula 5).

$$\% \, Error = \frac{[Exact \ value - Approximate \ value]}{Exact \ value} \ x \ 100 \quad (5)$$

In addition, we applied paired t-test with an alpha of 0.05 to see statistical significance differences between two variables. Firstly, we applied this statistical test with the variables, DBH and TL in the calibration plot as part of the methodology. Secondly, we applied this test to see the significant differences between volumes of supervised and unsupervised photo-interpretation.

3.8.2 Linear regression

Linear regression analysis is a statistical technique used to study the relationship between variables. This technique is widely used in forestry. The linear regression gives us a representation of points giving an idea of the relationship between the variables of interest. The simple linear regression has a very simple formula:

$$Y_i = B_0 + B_1 X_i \quad (6)$$

Due to this formula, it is possible to obtain the coefficients B_0 and B_1 through the least squares method. In addition, statistics of high importance are residual standard error, multiple R-squared, adjusted R-squared, F-static and P-value. Two linear regression were carried out to see the relationship between the ground truth against the supervised photo-interpretation. Later, we observed the relationship between ground truth against unsupervised photo-interpretation. We decided to use linear regression because is a suitable tool to compare our methods and see how our estimates of our photo-interpretation methods fit respect to our data from ground truth and see the relationship between the two variables, being important to us determinate the best fitting line between supervised and unsupervised photo-interpretation. Additionally, a theoretical line was included in order to have a better interpretation and see graphically how far our values obtained in both methods were respect to ground truth.

4. RESULTS

4.1 Comparison of volumes with supervised and unsupervised photo-interpretation

The results (Table 8) show some differences between the methods of supervised and unsupervised photo-interpretation.

Table 8. Total volume (m^3) with the three methods in each area

ID Area	Ground truth	Supervised	Unsupervised[11]	% Error S	% Error US
4	1929	667	1342	65.4	30.4
14	245	148	237	39.5	3.2
15	3092	2165	3576	29.9	15.6
16	175	140	118	20.0	32.5
17	842	741	1208	11.9	43.4
18	313	235	275	24.9	12.1
20	11980	4286	11861	64.2	0.9
22	258	208	432	19.3	67.4
23	553	440	480	20.4	13.2
36	186	117	43	37.0	76.8

It is important to remember that the ground truth volumes represented the control data. In the case of six of the ten areas of study, the unsupervised photo-interpretation showed better results in comparison with supervised photo-interpretation. In some cases, as in the area 20 the volumes were very close to the control data (Figure 22). However, the unsupervised photo-interpretation method overestimated the volumes in three areas (15, 17 and 22) and in the area 36, which had extremely small volume. On the other hand, the supervised photo-interpretation method systematically recorded smaller volumes. The volumes of the ten areas were underestimated. In some areas very far away from the volumes of ground truth for instance in the area 20, the volume obtained in ground truth was 11,980 m^3, but in supervised photo-interpretation was just 4,286 m^3. Other major differences occurred in the areas 4, 14 and 36.

[11] The results of unsupervised photo-interpretation were published as a conference paper in the international archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLI-B7, 2016 XIII ISPRS Congress, 12-19 July 2016, Prague, Czech Republic

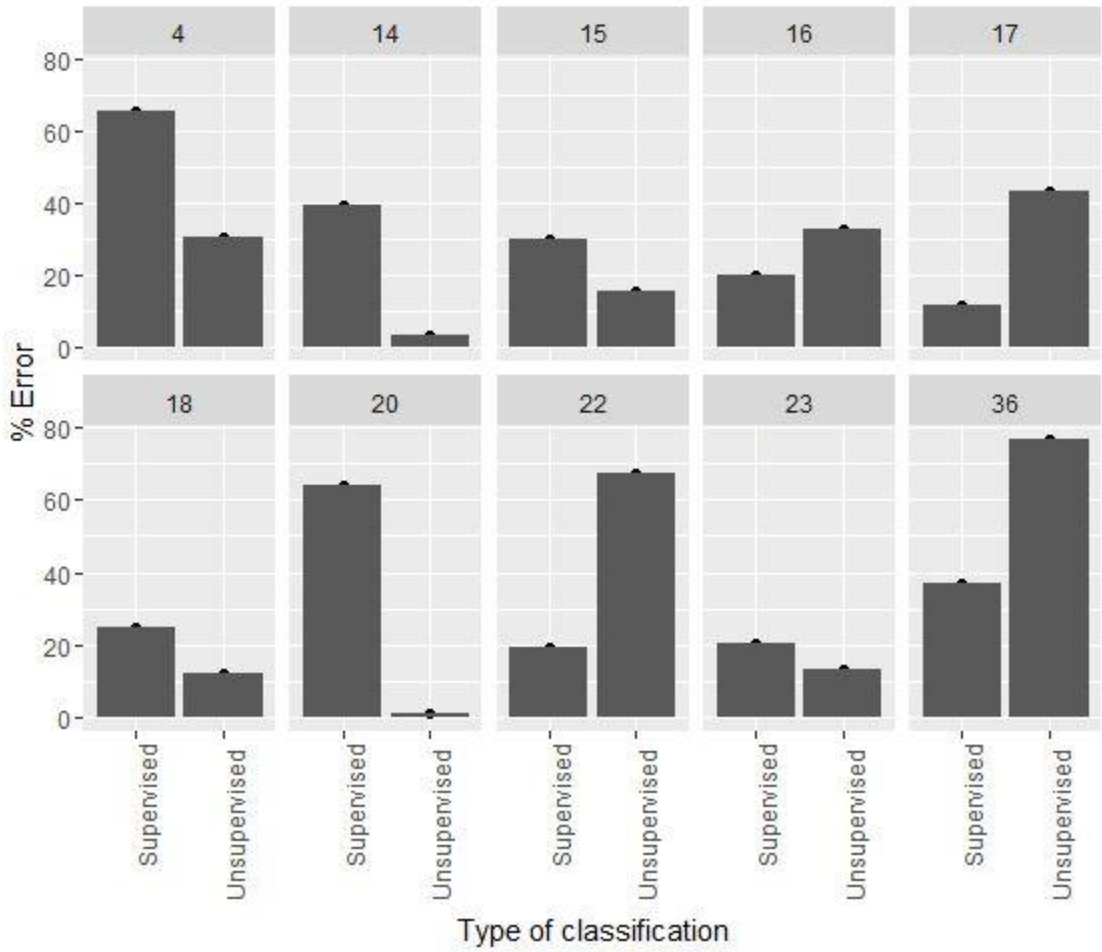

Figure 22. Bar plots comparing the percentage of error according to the type of classification

4.2 T-test paired two sample for means comparing supervised and unsupervised

According to the paired two samples t-test for the means, we cannot reject the hypothesis regarding the null difference between both methods. Thus, there were no statistically significant differences in the ten observations between the methods of supervised and unsupervised photo-interpretation. We arrived at a p-value of 0.192 (P(T<=t) two tail) with the means of these two variables showing a difference of 1,042 m^3. This clearly demonstrates a high difference between the volumes of both methods though mainly influenced by area 20 since the rest of the areas showed no major differences. In addition, the dispersion of the volumes was much higher with the supervised photo-interpretation method, it means that these volumes obtained a higher spread with respect to the mean (table 9).

Table 9. T-test paired two sample for means between volumes of supervised and unsupervised photo-interpretation

Statistics	Supervised	Unsupervised
Mean	914.7	1957.2
Variance	1781279.12	13221066.4
Observations	10	10
Pearson Correlation	0.98196808	
Hypothesized Mean Difference	0	
df	9	
T Stat	-1.40934933	
P(T<=t) one tail	0.09616777	
T Critical one tail	1.83311293	
P(T<=t) two tail	0.19233554	
T Critical two tail	2.26215716	

4.3 Linear regression comparing supervised and unsupervised against ground truth

In the comparison between supervised photo-interpretation and ground truth, the volume differences were quite significant and clearly noticeable when compared with an ideal line (red) in the regression analysis, which formed part of a theoretical line that does not use any dataset. The theoretical line just makes mention that the data between the variables that are under comparison should be the same. That is to say, the difference between the values that we are comparing must be Zero (0). The tendency that the supervised photo-interpretation line not matching so well with the ideal line results in the large differences in volume between supervised photo-interpretation and ground truth (figure 23). One of the main reasons why the lines parted ways is due to the area 20, where the volume difference between ground truth and supervised photo-interpretation was of 7,694 m^3.

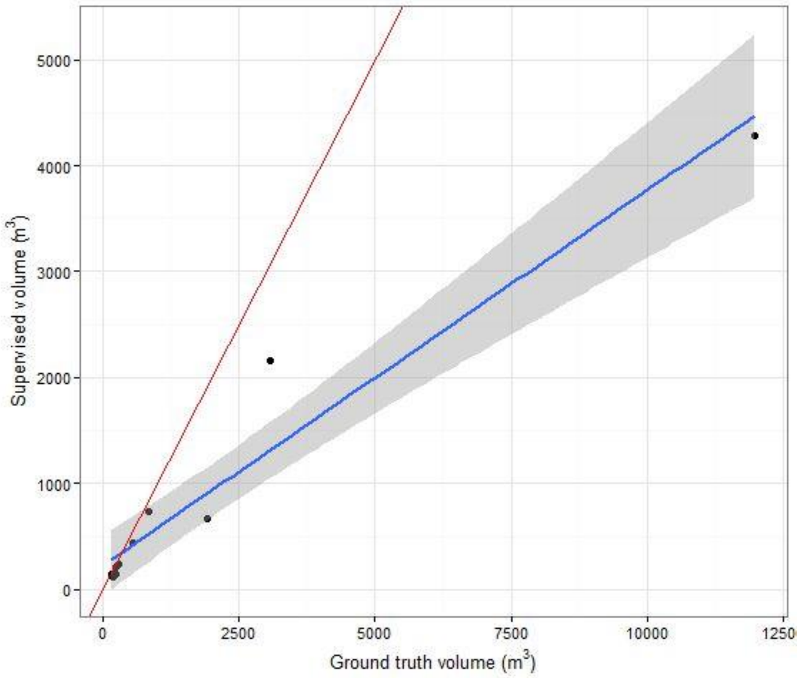

Figure 23. Linear regression between supervised photo-interpretation volume (m^3) and ground truth volume (m^3)

The volumes showed a positive relationship according to coefficient of correlation of Pearson reaching a value of 0.940. This R-squared showed that the data is fitting quite well though there are large differences in volume between both methods like in the area 20. The residual standard error is the measure of the quality of a linear regression fit. It gives meaning to the mean. That is to say, the response variable has deviated from the true regression line, with a value of 345.2 (table 10).

Table 10. Regression statistics of the total volume (m^3) by supervised estimation

Regression statistics	Supervised vs Ground truth
Residual standard error	345.2
Multiple R-squared	0.9405
Adjusted R-squared	0.9331
F -statistic	126.5
p-value	3.50E-06

The comparison between unsupervised photo-interpretation and ground truth shows better positive relationship according to the coefficient of correlation with respect to supervised photo-interpretation of a higher R-squared value of 0.993. The theoretical line (red), showed how close this line was with respect to the line got with our data (blue), the difficulty in distinguishing both lines in the graph (figure 24) and making a clear difference regarding the graph obtained with supervised photo-interpretation, where the theoretical line showed a completely different direction.

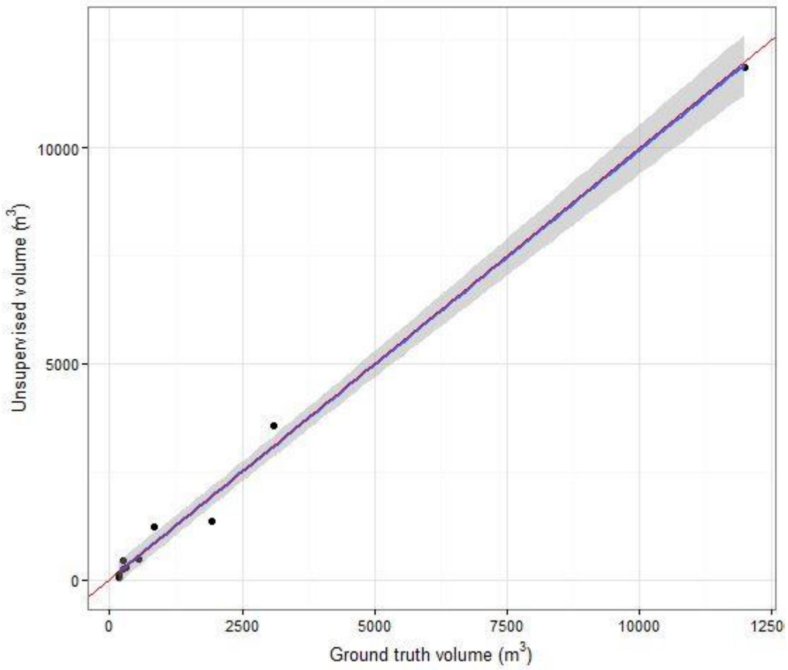

Figure 24. Linear regression between unsupervised photo-interpretation volume (m^3) and ground truth volume (m^3)

A way to quantifying or explaining how close the mean of the response variable has deviated from the true regression line is the residual standard error. This gives a better value with respect to supervised photo-interpretation. The value corresponded to 312.7 (table 11), comparatively lower when juxtaposed to the value obtained in the previous table which was 345.2.

Table 11. Regression statistics of the total volume (m^3) by unsupervised estimation

Regression statistics	**Unsupervised vs Ground truth**
Residual standard error	312.7
Multiple R-squared	0.9934
Adjusted R-squared	0.9926
F -statistic	1209
p-value	5.13E-10

4.4 Comparison of mean diameter between supervised and ground truth

Since the procedure of measuring the diameters involved the same protocol employed for sampling for the supervised photo-interpretation and ground truth, we decided to compare the mean diameters. This is because the same piece of wood was measured twice using both techniques and the results tested to verify the accuracy of the data obtained in the calibration plot.

Systematically, the mean of the diameters of supervised photo-interpretation were slightly higher, with a maximum difference of 3 cm and a minimum of 0.5 cm. However, in terms of dispersion of the data, they were more heterogeneous with the coefficient of variation (CV) showing slight differences yet not systematic. The CV was higher in the ten areas as in the mean diameter with supervised photo-interpretation. Six of the ten areas of study showed higher CV in ground truth with the highest difference in the area 16, where the CV obtained in ground truth was 13.5% and in supervised photo-interpretation was only 7.2% resulting in a difference of 6.3%. The rest of the study areas had mean difference of only 2.1% (table 12). On the other hand, the range of the percentage error of the supervised photo-interpretation with respect to ground truth were very low. None of the ten areas exceeded the 10%. The maximum percentage error (9.5%) was in the area 20 while the lowest percentage of error (1.5%) was in the area 14. We assumed that, the greater is the number of samples measured, the greater the percentage of error as in the area 20, where 647 samples lines were measured in the supervised photo-interpretation.

Table 12. Comparison of the mean diameter of ground truth and supervised photo-interpretation

	Ground truth				Supervised				Error
ID	Mean	SD	Variance	CV%	Mean	SD	Variance	CV%	(%)
4	32.8	3.9	14.9	11.8	35.1	4.8	23.1	13.7	7.0
14	32.1	3.4	11.7	10.7	32.6	3.9	14.9	11.9	1.5
15	31.6	3.7	13.7	11.7	33.6	3.5	12.0	10.3	6.3
16	28.9	3.9	15.2	13.5	31.3	2.3	5.1	7.2	8.3
17	30.1	3.1	9.7	10.4	31.8	2.9	8.1	9.0	5.6
18	33.1	3.4	11.7	10.3	34.4	3.3	10.9	9.6	3.9
20	30.4	3.7	13.6	12.1	33.3	3.9	15.4	11.8	9.5
22	35.9	3.6	13.3	10.1	38.5	4.1	16.8	10.6	7.2
23	35.7	5.8	34.2	16.4	38.7	4.8	23.3	12.5	8.4
36	33.6	3.4	11.3	10.0	34.3	4.7	21.6	13.6	2.0

Graphically, it can be demonstrated that, difference between the measurements made in ground truth and supervised photo-interpretation, did not show statistically significant differences between the mean diameters by the paired two samples t-test for the means (figure 25). The p-value was very small (6.29391E-05). The average mean diameter of ground truth and supervised photo-interpretation in the ten study areas was 32.4 cm and 34.3 cm respectively giving a difference of just 1.9 cm. Since an accepted percentage error is 10% in majority of inventories, this difference is without doubt very small.

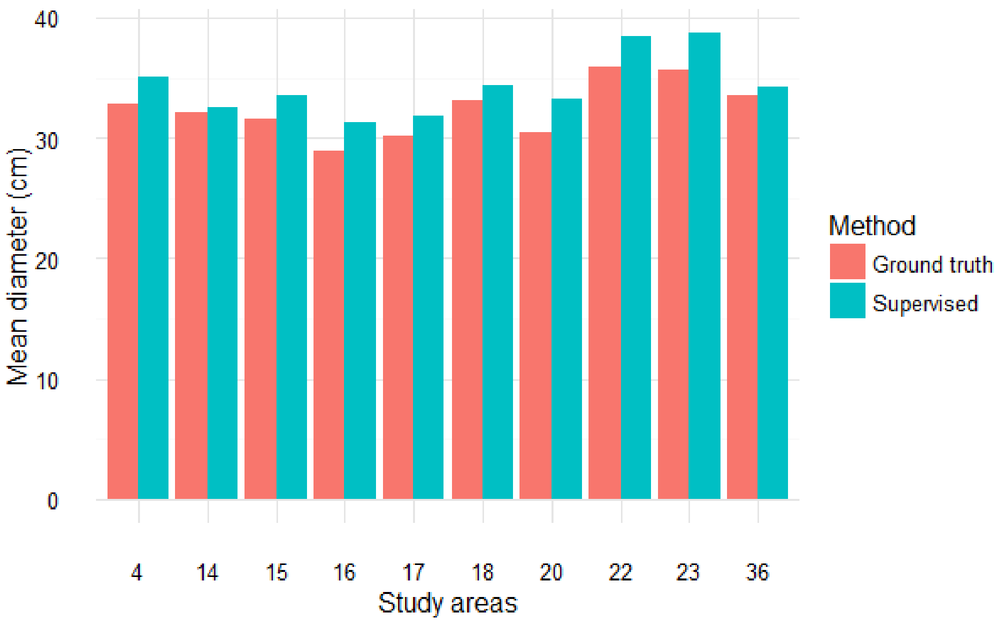

Figure 25. Histogram comparing the mean diameter between ground truth and supervised photo-interpretation

4.5 Comparison of number of intersections between ground truth and supervised

As with the mean diameter, the data obtained with the count of intersections showed a systematic relationship. In the ten areas of study, the ground truth showed higher number of intersections in comparison with supervised photo-interpretation. The percentage of error was between 23.8 and 54.5%. The data showed was highly reflective of the plot area. In the smallest area (1.1 ha), we recorded the highest difference (54.5%), while in the biggest area (25.9 ha) we got the smallest percentage of error (23.8%).

Table 13. Comparison of the number of intersections between ground truth and supervised photo-interpretation

ID	Ground truth	Supervised	Difference	% Error
4	388	216	-172	44.3
14	115	57	-58	50.4
15	1258	746	-512	40.6
16	95	58	-37	38.9
17	446	294	-152	34.0
18	134	79	-55	41.0
20	2017	1535	-482	23.8
22	99	56	-43	43.4
23	204	119	-85	41.6
36	88	40	-48	54.5

The number of intersections is very important for the total volume since the volume directly relates to the number of measurements made by each single line. Figure 26 explains why the supervised photo-interpretation method recorded a very small volume with a 41.2 mean percentage of error obtained in the ten areas. This is an extremely high value when it comes to obtaining more volumes that are precise. Lastly, it is important to mention that the volumes all the sample lines with 0 intersections (figure 18) were obviously considered as 0 m^3. This resulted in a large decrease in the final mean volume in each of the study areas. The main reason why the volumes obtained by supervised photo-interpretation were very small was the difficulty in recognizing the exact number of intersections. This brings to bear that one of the weaknesses of the supervised photo-interpretation in combination with LIS is that from the air with the image, the photo-interpreter is not able to recognize log under the crowns (branches on the logs prevent their visualization).

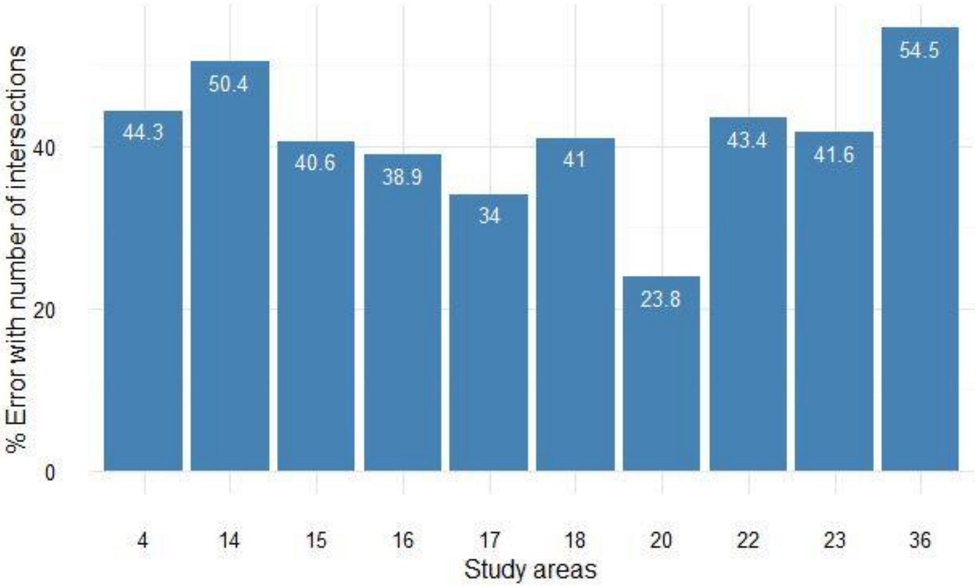

Figure 26. Histogram comparing the number of intersections between ground truth and supervised photo-interpretation

5. DISCUSSION

Field surveys of dead wood using LIS can be inefficient, dangerous to the operators and expensive. Nowadays more efficient technologies are preferred. The quantification of dead wood has increased in importance in most countries. According to Ritter and Saborowski, (2012) thirty countries (21 are European) worldwide conducted inventory on dead wood and only 12% used LIS. This gives an indication that LIS is probably an inefficient method for taking inventory e.g. assessing winthrow damages. However, the same authors mentioned that LIS is a superior method for sampling CWD as compared to other field-assessed inventory methods such as Point Transect Sampling (PTS) or Fixed Area Sampling (FAS). The PTS and FAS methods show some practical problems, mainly related to the weather conditions e.g. snow presence coupled with dense ground vegetation complicates the sampling work when it comes to FAS. On the other hand, the possibility of multiple counting is very high with respect to the PTS method hence requires proper care and attention. Probably, a big disadvantage of LIS method when it comes to windthrow is the direction at which the trees fall. An overestimation of volume by the LIS method occurs in the case where trees follow the same pattern at the moment of falling and if the lines are perpendicular to the downed dead wood log when using the variables, direction of the wind and slope (in the step terrains) (Pesonen et al.

2009). On the contrary, if the lines are parallel to the logs, the probability to intersect with fallen trees will be very low leading to an underestimated volume. The above anomaly is also known as Buffon’s needle problem and is described more in detail by Kleinn (2007). Another drawback of the LIS is that, it unable to include standing dead trees affected by windthrow in the sample line. Regardless of these drawbacks, Ritter and Saborowski (2012) recommended LIS as the best traditional method to sampling CWD. However, according to the results obtained in our investigation, LIS does not prove to be a superior method with respect to PTS and FAS as earlier mentioned by Ritter and Saborowski (2012). In our research, LIS demonstrated to be a methodology very dependent on the terrain conditions, showing a number of drawbacks for estimating dead wood according to a particular condition. Other important aspect to mention is that according to the literature, LIS is a practical method on the field, considering certain assumptions and that was the main reason why we chose this methodology in this research. However, the conditions change substantially when the work is on the field or through an image. Thus, it should be noted that many of the disadvantages of this method previously mentioned, are more linked in their application to a supervised photo-interpretation, than to capture data on the field with this sampling method.

All the same, LIS could be replaced by new sampling techniques through remote sensing however will still not be an efficient method for new challenges such as windthrow. Terrestrial laser system (TLS) presents a potential alternative method for LIS as proposed by Astrup et al. (2014) to estimate volume using TLS. The TLS yielded better results as compared with standard ground based inventory estimates hence can be applied to quantify dead wood or ALS. Pesonen et al. (2008) mentioned that ALS can be used to produce quite accurate estimate of fallen dead wood volume and not standing dead trees, where accuracy will be lower. Nevertheless, although these new methods based on remote sensing tools appear as highly tentative alternatives, the cost of their acquisition remains as a limiting factor in order to apply those methodologies in an operational scale. As has been mentioned by Nyström et al. (2014), a manual photo-interpretation is very time consuming, therefore, the next step should be to automate photo-interpretation. Detection of dead wood from remotely sensed data is quite difficult because the undergrowth and treetops prevent a good approach to the object of interest. This happened in our supervised photo-interpretation where several logs were missing because this. Furthermore, the automatic method could confuse lying stems with stones or walls (Lindberg et al. 2013). The main goal of the automatic method is to identify if the pixel belongs to a dead wood or not. With regards to our supervised photo-interpretation, we excluded not so clear intersections in order to avoid an incorrect photo-interpretation of the objects to be measured.

Chirici et al. (in press) carried out their research in the same ten studies areas with the main goal to identify a simple method to estimate the volume of the dead wood after windthrow through two-stage sampling strategy using single-date. The research work yielded very successful results with the estimation of dead wood in the damaged areas using ALS as has been demonstrated by Chirici et al. (2016). Additionally, Nyström et al. (2014) applied a similar methodology with ALS using differences between two elevation models. The method consisted in an automatic detection of windthrown trees using template matching. Others works were carried out using ALS in order to develop an automatic method to detect storm damages. Honkavaara et al. (2013) showed that photogrammetric and ALS data are practical tools for automatic detection in forest storm damage classification which yields very good results. Just as with our unsupervised photo-interpretation, ALS is a cost-efficient method for mapping wide areas, but this methodology of automatic detection is too sensitive to detect small areas damages (∼1 ha). It reflected in our results in the biggest area (20) with very similar values between ground truth and unsupervised photo-interpretation, but not very accurate in small areas (area 36). The automatic method tends to overestimate volumes in the small areas (areas 22 and 17), with errors of 67.4 and 43.4% respect to ground truth.

The ALS-based estimate of fallen trees volume by Chirici et al. (in press) obtained a range between 1.9 and 22.8 with the relative standard error (%), similar results has been obtained by Pirotti et al. (2016) using RGB images with high resolution. The volumes with ALS were very close to the volumes obtained with ground truth and more or less similar with the unsupervised photo-interpretation, but quite far from the supervised photo-interpretation. This confirms that the results obtained through supervised photo-interpretation were the worst in all the aspects since it is time and cost intensive, as it requires an experienced photo-interpreter (Anttila, 2002). Several studies conducted compared field measurements with supervised photo-interpretation in the Nordic countries and have revealed a bias ranging between -22 and 39%. The greater errors were identified in photo-interpretation compared to field measurements. On the other side, Eid et al. (2004) mentioned that the parameters for stand inventories as basal area, dominant height and number of trees per hectare were more precise with laser scanning based on a two-stage procedure than with a manual stereoscopic measurements done by photo-interpreters. Although the comparison made by Eid et al. (2004) is related to an inventory of standing trees (in order to carry out a supervised photo-interpretation in the estimation of dead wood is even more complicate, since more details and precision are required from the images in comparison with a plot of standing trees), matched with the results obtained by Pirotti et al. (2016) and Chirici et al. (in press) in the estimation of dead wood after windthrow, where was identified that it is more precise to use an automatic method than a supervised photo-interpretation in order to quantify the dead wood after the disturbance as our results have shown.

The method applied by Chirici et al. (in press) with ALS was used to delimit the damaged areas and to estimate the total volume of the fallen tress through of a model-assisted approach. Result obtained on plot 20 were better, obtaining a volume of 497.0 m^3/ha, although this value overestimates a little on the value of ground truth (462.9 m^3/ha), but the relative standard error (%), was only 1.9. Something similar happened with the results of our unsupervised photo-interpretation, where the volume was 458.3 m^3/ha, obtaining only a percentage of error 0.9 respect to the value of ground truth. On the other hand, the worst results were in the study areas 16, 14 and 22 with a relative standard error (%) of 22.8, 21.3 and 19.3 respectively. The results of Chirici et al. (in press) shown a similar tendency of our results, especially with the unsupervised photo-interpretation method, where the error is directly influenced by the area of the plot, between bigger is the plot, smaller is the error, being opposite with the small plot, where the tendency is that between smaller is the plot, higher is the error. However, ten areas of study probably are not enough to determinate that through ALS we can replace the field work. Investigations carried out by Naesset (1996), Eid and Naesset (1998) or Eid et al. (2004) included in their respective methodologies for standard forest inventories at least a range between 77 and 333 stand were used in the evaluation between field measurements and photo-interpretation, being values much higher than those used in our methodology, due mainly to the limitation of LIS measurements in the field. The number of plots and the size of them are somehow linked in the results, in the small areas the error was quite high, but in the only one big area used, the result obtained was quite good, but considering just one big area of study is not enough to make conclusions that this method is suitable for big stands. Therefore, there is no clear trend in this regard, in order to confirm that bigger areas the error will be lower, it is necessary to replicate the automatic method in a higher number of plots. There is no much literature regarding how the size of the plots affect to the specific issue of the estimation of the dead wood through LIS, but there is some investigation related to number of stems, basal area and timber volume about forest with standing trees, where according to Naesset (2002), using airborne laser scanning with two-stage procedure, small plots will be influence most seriously by such uneven distribution over a larger area, being evident with our results. The plots in our research were also heterogeneous respect to the level of damage, some small plots only suffered half of damage by windthrow (area 16), while other plots suffered damage practically in their total area (area 36), being a very important and influential characteristic in small plots for the estimation of volume (see appendix). Therefore, according to Naesset (2002) the size of the plot should not be too small, it can be an explanation why the unsupervised photo-interpretation was not very successful in the small areas. However, the problem to extend the plot size is that it could increase the cost of the operations in the field. This last consideration regarding the operational cost was the main motivation to deal with small plots in our methodology, due mainly for the high cost in obtain the control data.

The reason why the supervised photo-interpretation got the worst results was mainly one. The interpretation of objects as fallen trees in an image is easy for the human eye (Ballard and Brown, 1982). Nevertheless, within the context of windthrow, the application of LIS in a supervised photo-interpretation is too complicate, because no matter how good the image quality is, while the tops of the trees will be over the fallen logs, the total volume always will be low. The quality of the digital orthophotos with 0.2 m spatial resolution were good enough in order to carried out a supervised photo-interpretation in our research, even if the object to measure was very small. Our results have shown that the difference between the mean diameter obtained by ground truth and supervised photo-interpretation was minimum. The main issue was the identification of all the objects to be measured, some of them were hidden under the top of the trees, as our result have shown between the total intersection count obtained by ground truth and supervised photo-interpretation. In other scenarios, where the forest belongs to standing trees, the result is different because there are no other components of the trees that overlap on the object to be measured. Magnusson et al. (2007) showed that in variables such as estimation of stem volume, tree height and tree species composition it is possible to obtain accurate information through aerial photo-interpretation. However, in scenarios such as windthrow, the application of a sampling method as LIS is not suitable for carried out a supervised photo-interpretation, being more convenient the application of an automatic method, as is demonstrated by Pirotti et al. (2016) with RGB images or by Chirici et al. (in press) through ALS.

6. CONCLUSION

Our results showed that the unsupervised photo-interpretation got better results than supervised photo-interpretation. However, the method of kernel normalized cross-correlation as an automatic method to quantify the volumes of dead wood through pixels was quite inconsistent. The worst result with the unsupervised method has been achieved in the case of the smallest area of study (36), where the total volume was much lower than the control data, obtaining only 43 m^3 compared to ground truth, 186 m^3. Nevertheless, surprisingly with the biggest area, the volume obtained was very accurate, with a % of error of 0.9 respect to our control data. Our study cannot demonstrate that unsupervised photo-interpretation is accurate with big areas of forest because we got just one big area of the ten selected. Thus, it would be very hasty to conclude that this method is appropriate for large forest areas, since it could be only a coincidence. However, it is promising result that allows to continue with this line of investigation and go deeper with others big study areas and see if the results keep a consistent tendency.

The results of supervised photo-interpretation were consistent, but negatively, where in the case of all ten areas, always showed values much lower comparing with the control data. The reason why the volume was systematically lower with supervised photo-interpretation can be explained though the number of intersections. In fact, in our research we tried to identify the main issue with this methodology, the working hypothesis was that the measurements of the diameters were underestimate, but the answer was negative and actually the diameters obtained by the supervised photo-interpretation were slightly overestimating respect to the values from ground truth.

Once, we verified that the problem was not related to the measurement of the diameters. We noticed that the number of trees counted by each single line, was higher in the ten study areas in comparison with ground truth, demonstrating that the main issue with the methodology of supervised photo-interpretation, is that though LIS is not possible to identify all the trees that intersect the sample line though RGB images with very high resolution (0.2 m GSD). The methodology of supervised photo-interpretation has shown that the bigger is the polygon, the higher is the number of intersections that are missing (demonstrated in the study area 20). Thus, the fact of identifying a smaller number of intersections, will give always a lower volume of dead wood, impairing significantly their estimation. Probably, some logs that remain under the crowns were not part of the total sample at the moment of calculating the volume with this methodology, losing valuable information.

The fact that supervised photo-interpretation had a systematic tendency to underestimate volumes, it is possible that a supervised photo-interpretation with analysis techniques of 3D remote imagery could improve the recognition of logs that previously was not accounted. Consequently, as the number of intersections increased, dead wood volume will increase. Approaching the volumes from the supervised photo-interpretation with the volumes from ground truth. In this approach, should be important not overestimate the volumes as happened in some plots with the unsupervised photo-interpretation. It is important to mention that, for practical purposes in a forest inventory, it is always better to underestimate than to overestimate, for the simple reason that timber buyers do not want to pay for a product that technically does not exist in the forest trade.

From this work, we can suggest some ideas. Fieldwork is highly expensive and time consuming, even with the supervised photo-interpretation, where is necessary to pay to an experienced photo-interpreter, who will spend a considerable time on it. The method called kernel normalized cross-correlation could be applied in more plots with bigger areas and try to analyze if the results are consistence with at least a number of plots that allows to validate the information according to the most recent literature, where the study areas can be substantially bigger than the areas used in this work, in order to test the method properly. In case that the results are positives, this method can be very useful to quantify damages after windthrow at regional and national scales in a very effective way, when a rapid approximation in the quantification of the damage is required, in cubic meters as well as monetary.

Taking in consideration that this automatic method is not very accurate in small areas, supervised photo-interpretation with technology in 3D can be a potential solution at small level. However, in areas very small < 1 ha. The high costs of acquiring good quality images (a flight in order to obtain images LiDAR has a cost approximately of 10,000 Euros, being an unnecessary expense for a small area[12]) and the risk of not obtaining the expected precision. The technology ALS could be very expensive to carry out at small level. We recommended the classical method with field work though LIS, where areas about more or less one hectare will not have more than 30 lines, where easily this type of plot can be measure in one journey. Additionally, from this work we can be recommend go further with automatic method to quantify damages after windthrow and finally and according to our results have shown that it is not possible to carry out LIS in a supervised photo-interpretation, unless a photo-interpretation in 3D can improve the identification of the intersections with the samples lines.

7. SUMMARY

During the last 5 years, the region of Tuscany has suffered two windstorms in November, 2013 and March, 2015, causing big damages in forests. In order to quantify the damaged caused by the windthrow, local authorities were concern to determinate the volume of dead wood in all the region in the quickest possible time. The main objective of this research was focus in create a new methodology cost-effective to estimate the dead wood volumes post windthrow through remote sensing and geographical information system tools. Two methods were tested: 1) supervised photo-interpretation in combination with line intersect sampling and 2) unsupervised photo-interpretation called kernel normalize cross-correlation through RGB images, with a pixel size of 20 cm. Furthermore, field data was collected as a control data through line intersect sampling with the same protocol used in supervised photo-interpretation. The study was carried out in the northeastern part of Tuscany, in the provinces of Pistoia, Florence, Lucca and Arezzo. Ten study areas were selected, where the surfaces varied between

[12]Personal communication with Prof. Francesco Pirotti from University of Padova

1.1 and 25.9 ha. The species affected were mostly conifer species as *Pinus nigra* (black pine), *Abies alba* (silver fir) and *Pseudotsuga menziessi* (douglas fir), with a DBH between 22 to 57 cm. The unsupervised photo-interpretation obtained better results than supervised photo-interpretation, with a R^2 = 0.993. However, both methods did not show statistically significant differences (p-value = 0.192). Nevertheless, the errors obtained by the supervised photo-interpretation were unacceptable in mostly of the plots. On the other side, the automatic method got promising results comparing to ground truth data, but only in a big area, where showed an accurate volume. All the same, just one big study area is not enough to test the method. So, the automatic method must be replicated in a higher number of areas and with bigger surfaces respect to this study, in order to prove that this method can be useful for a quick estimation of dead wood post windthrow. Additionally, the automatic method demonstrated to be unsuitable for small areas, with high errors and with a tendency to overestimate the dead wood volumes. By last, supervised photo-interpretation was far from the expected results, concluding that a supervised photo-interpretation in combination with line intersect sampling was an inefficient method to deal the quantification of damages post windstorms according to the results obtained in this study. The main reason for the low volumes in the supervised photo-interpretation, was the difficulty in the identification of the intersections, converting it an inappropriate method, unless the photo-interpretation can be carried out with 3D technology.

8. SOUHRN

Během posledních pěti let bylo Toskánsko zasaženo dvěma vichřicemi, a to v listopadu roku 2013 a březnu 2015, kdy tyto vichřice v tamních lesích způsobily velké škody.
Aby bylo možné vyčíslit škody způsobené větrem, místní úřady potřebovaly co nejrychleji určit množství mrtvého dřeva v celém regionu. Hlavním cílem tohoto výzkumu bylo vytvoření nové cenově přijatelné metody odhadu množství mrtvého dřeva prostřednictvím dálkového průzkumu Země a geografických informačních systémů. Testovány byly dvě metody: 1) řízená fotointerpretace v kombinaci s liniovým výběrem (line intersect sampling - LIS) a 2) fotointerpretace neřízená (kernel normalize cross-correlation - NCC) pomocí RGB obrazů o vysokém rozlišení s velikostí pixelu 20 cm. Kromě toho byla terénním měřením získána kontrolní data s použitím stejného

výběrového protokolu jako u řízené fotointerpretace (line intersect sampling). Studie byla provedena v severovýchodní části Toskánska, a to v provinciích Pistoia, Florencie, Lucca a Arezzo. Bylo vybráno deset území o výměře 1.1 - 25.9 ha. Postiženými druhy byly hlavně jehličnany jako *Pinus nigra* (borovice černá), *Abies alba* (jedle bělokorá) a *Pseudotsuga menziesii* (douglaska tisolistá) se střední tloušťkou 22 až 57 cm. Neřízená fotointerpretace poskytla lepší výsledky oproti metodě řízené (R^2= 0,993). Mezi výsledky obou metod nebyl prokázán statisticky významný rozdíl (p-hodnota = 0,192), nicméně chyby získané řízenou fotointerpretací na některých plochách byly nepřijatelné. Na druhé straně, automatická metoda v porovnání s daty získanými přímým měřením v terénu měla slibné výsledky, avšak jen v případě velkých ploch. Ovšem na základě jedné studie není možné tuto metodu otestovat s dostatečnou spolehlivostí, proto by tato metoda měla být zopakována na větším počtu území s cílem prokázat, že může být užitečná pro rychlý odhad objemu mrtvého dřeva po vichřici. Navíc se automatická metoda ukázala jako nevhodná pro malé plochy, jelikož je zatížena velkým množstvím chyb se sklonem k nadhodnocení objemu mrtvého dřeva. Výsledky řízené fotointerpretace se u některých ploch velmi odlišovaly od dat získaných přímým terénním měřením. Hlavním důvodem odchylek byla obtížná identifikace průsečíků stromů s výběrovými liniemi na snímcích.

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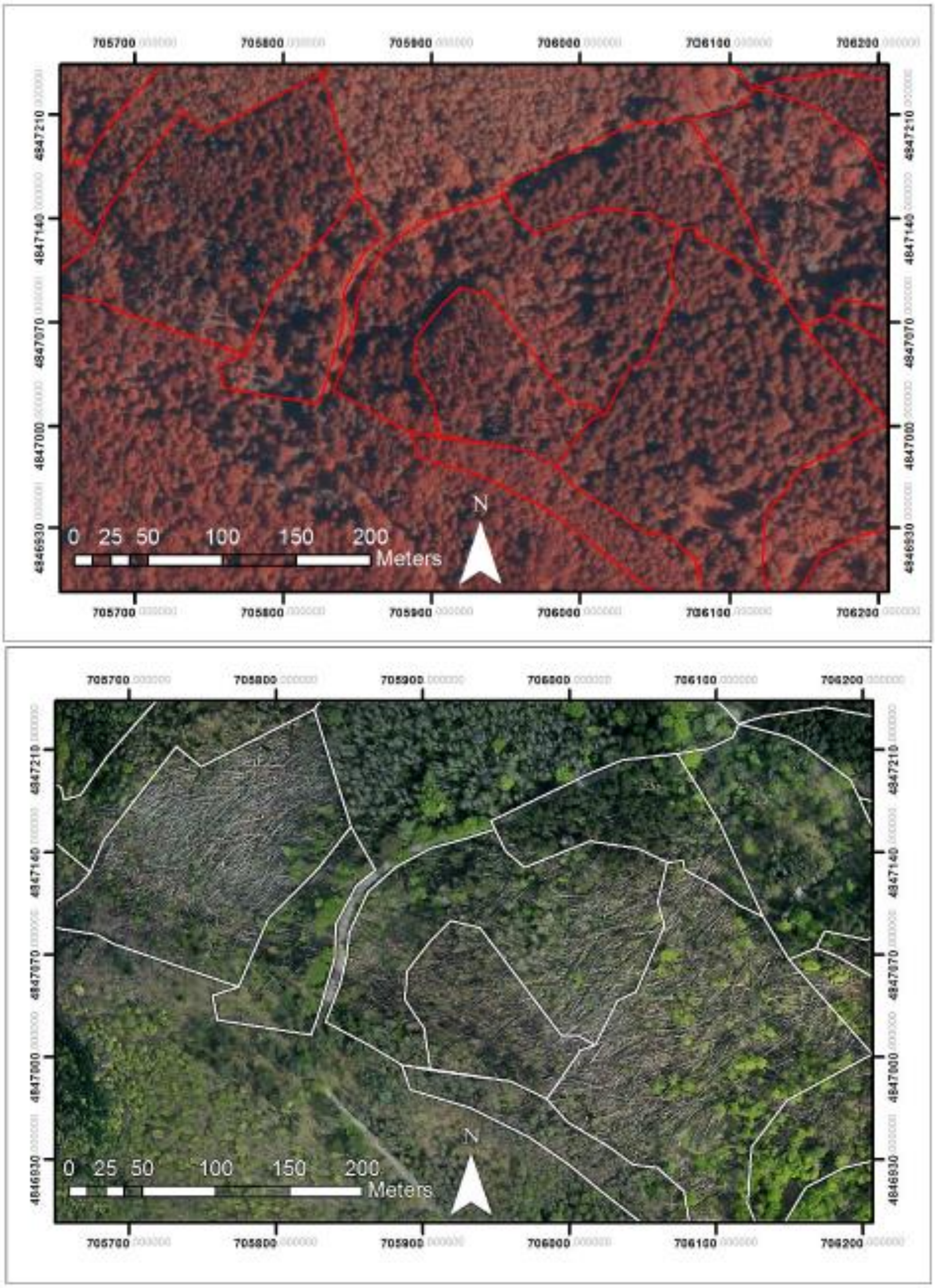
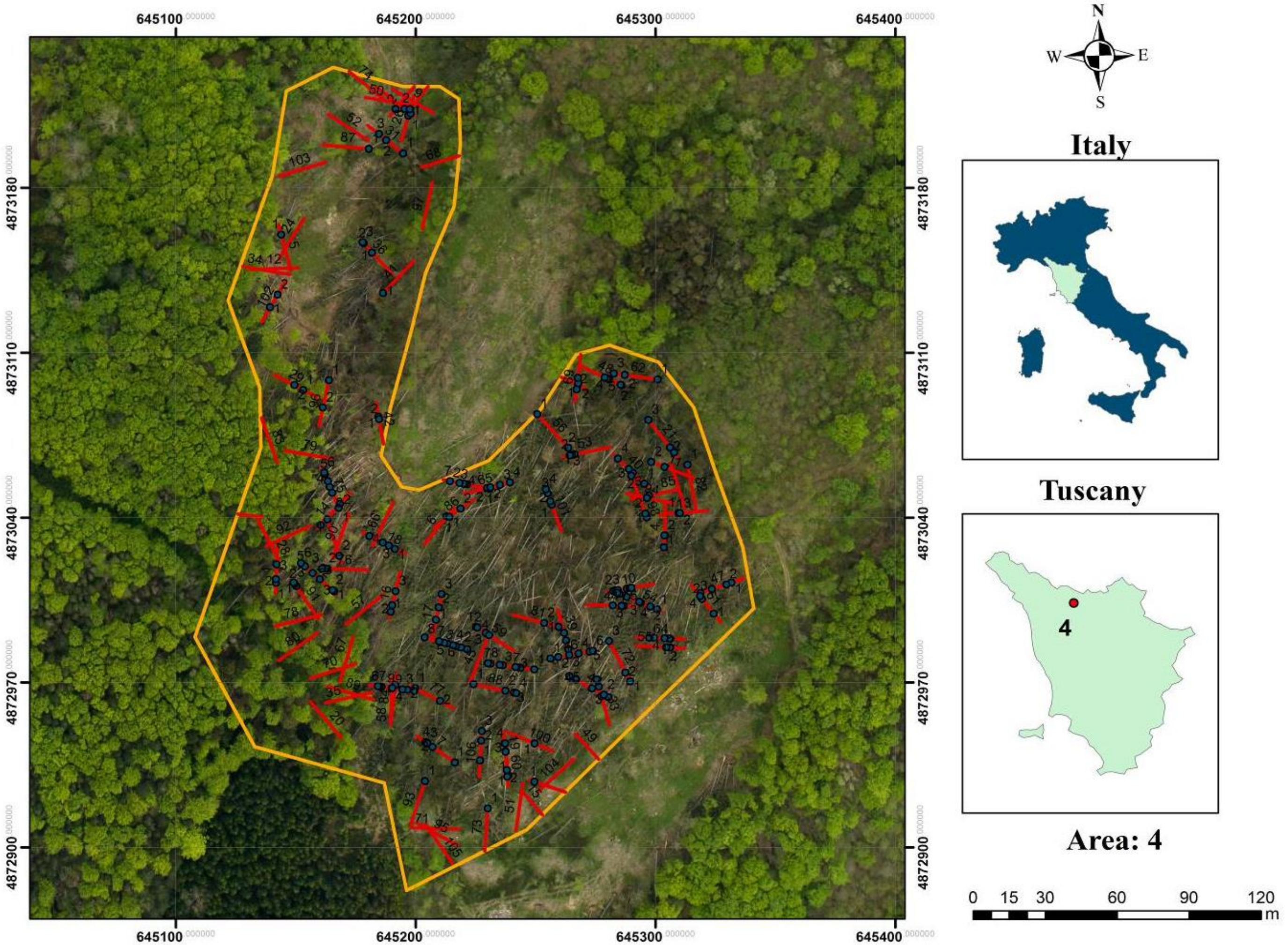
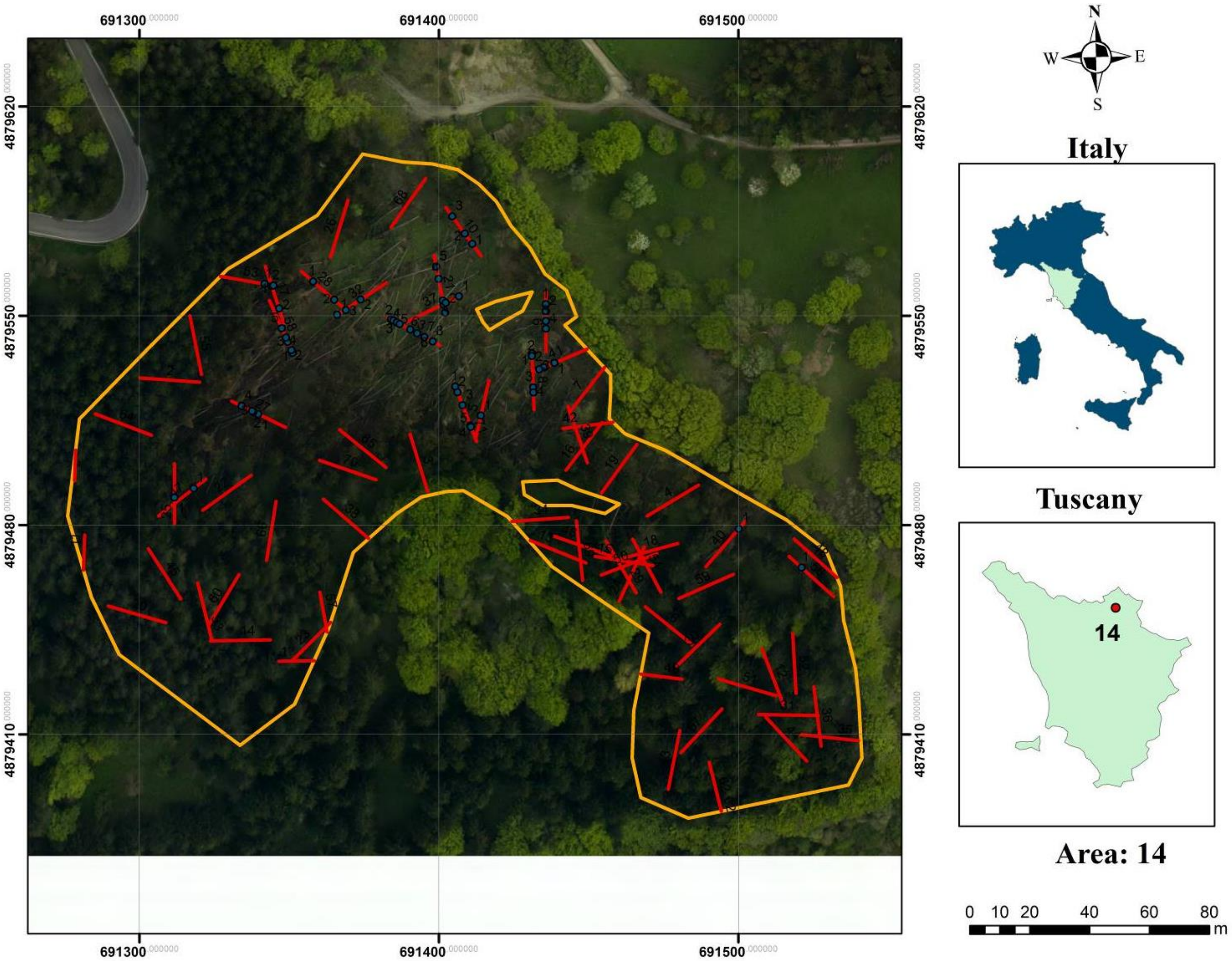
Appendix

Annex 1. Example of photo-interpretation pre and post windthrow (Chirici et al. 2016)



Annex 2. The ten study areas in the Tuscany region





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691500.000000
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4879480.000000
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W
E
S
Italy
Tuscany
14
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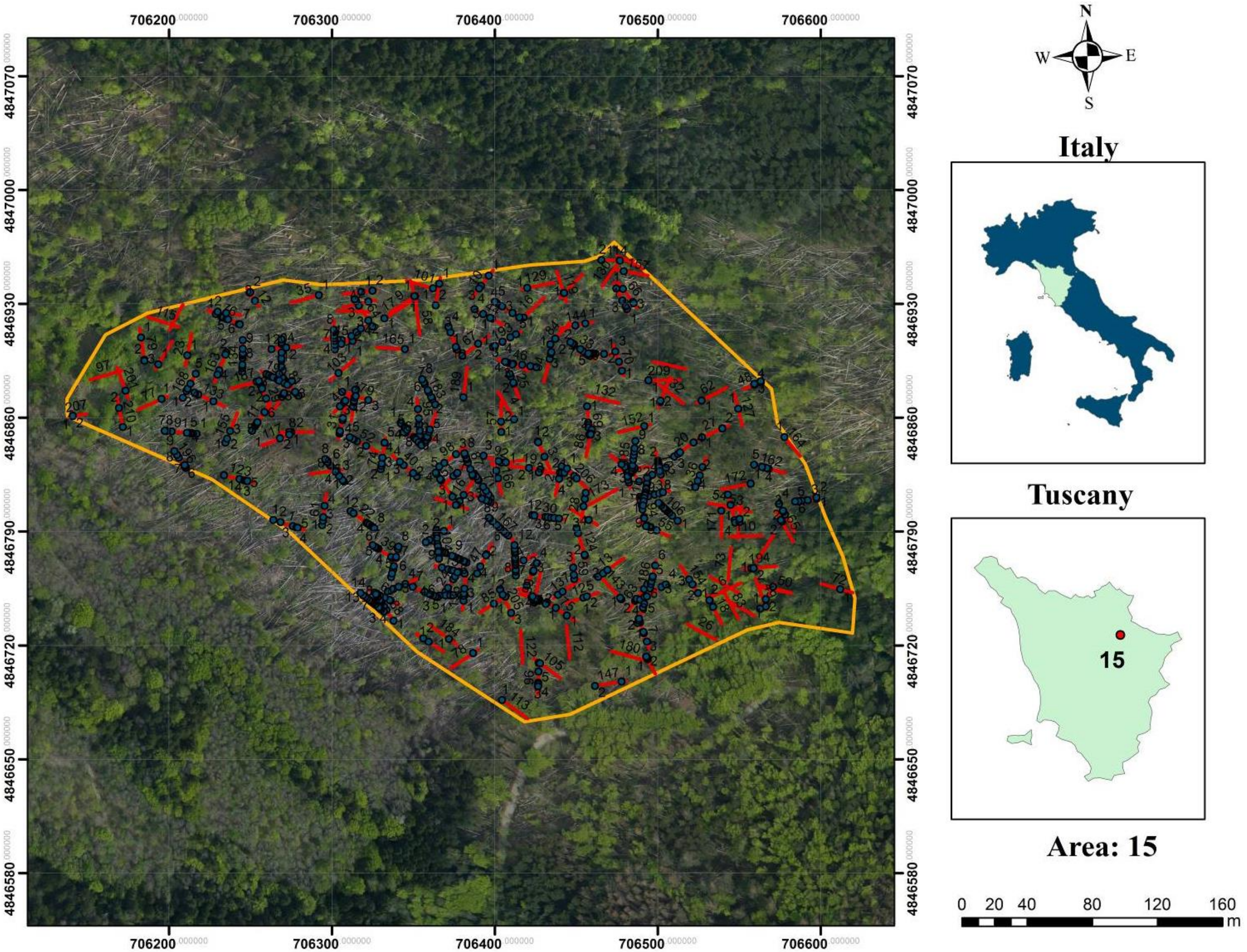
m



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S
Italy
Tuscany
15
Area: 15
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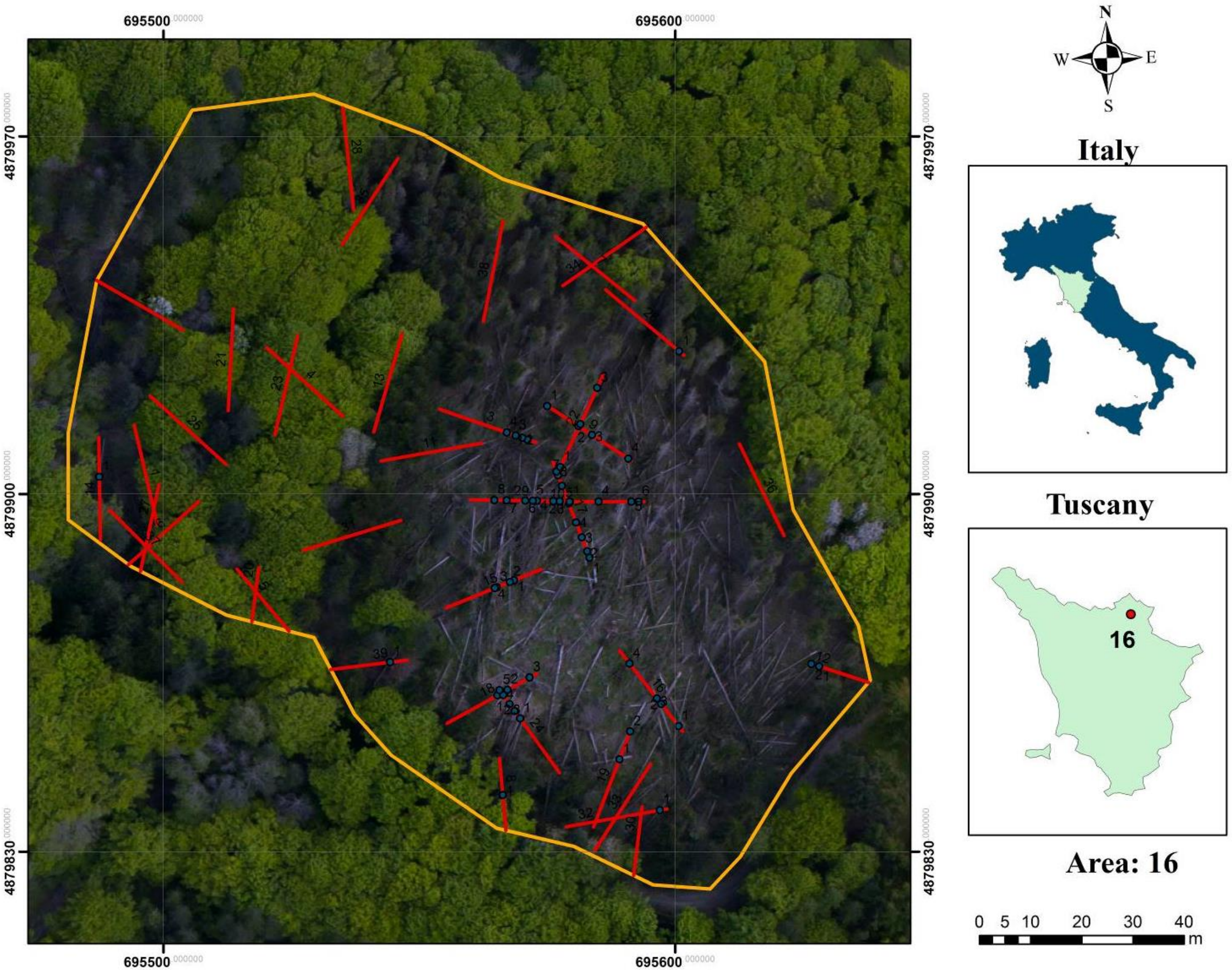
m



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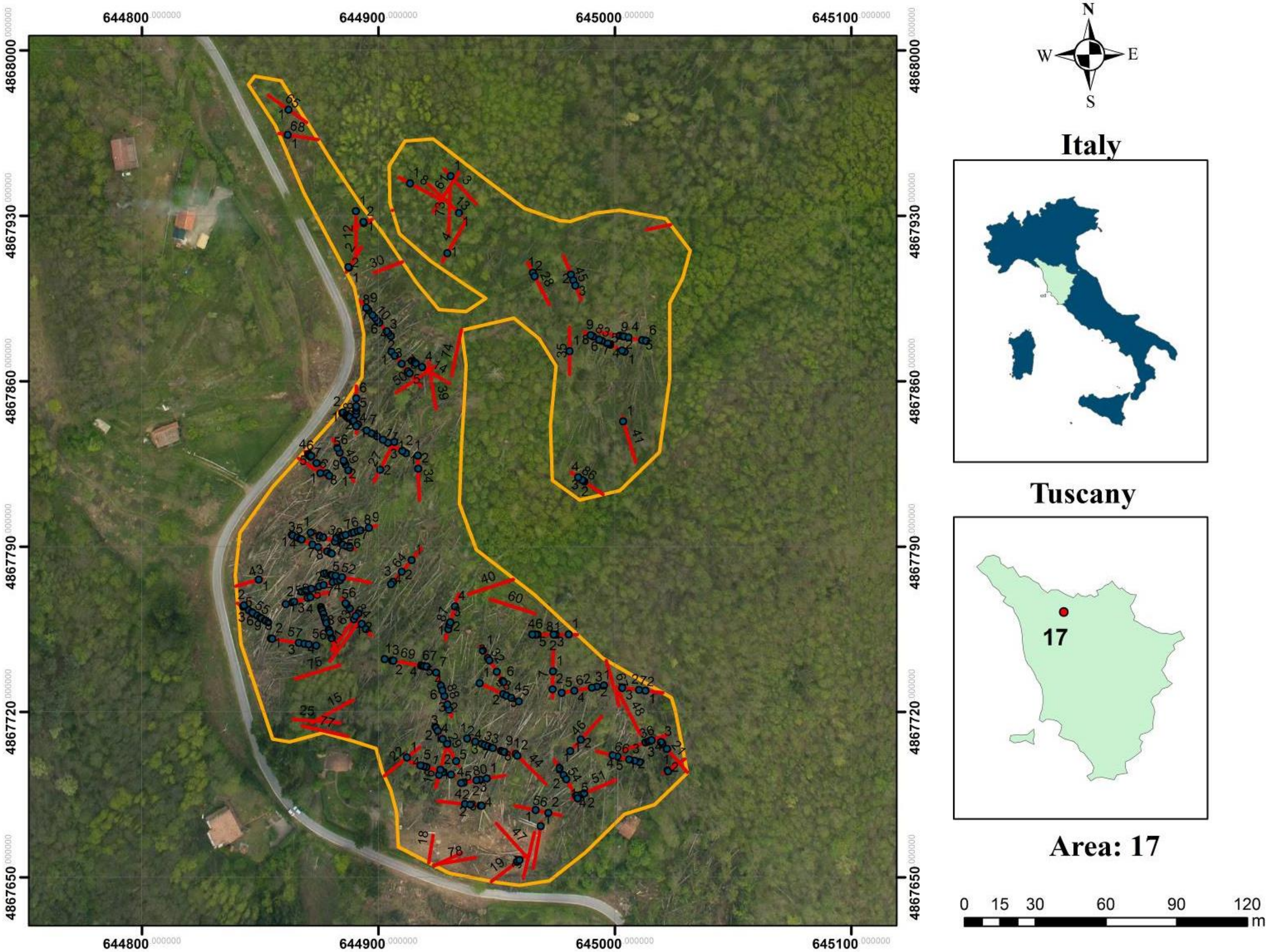
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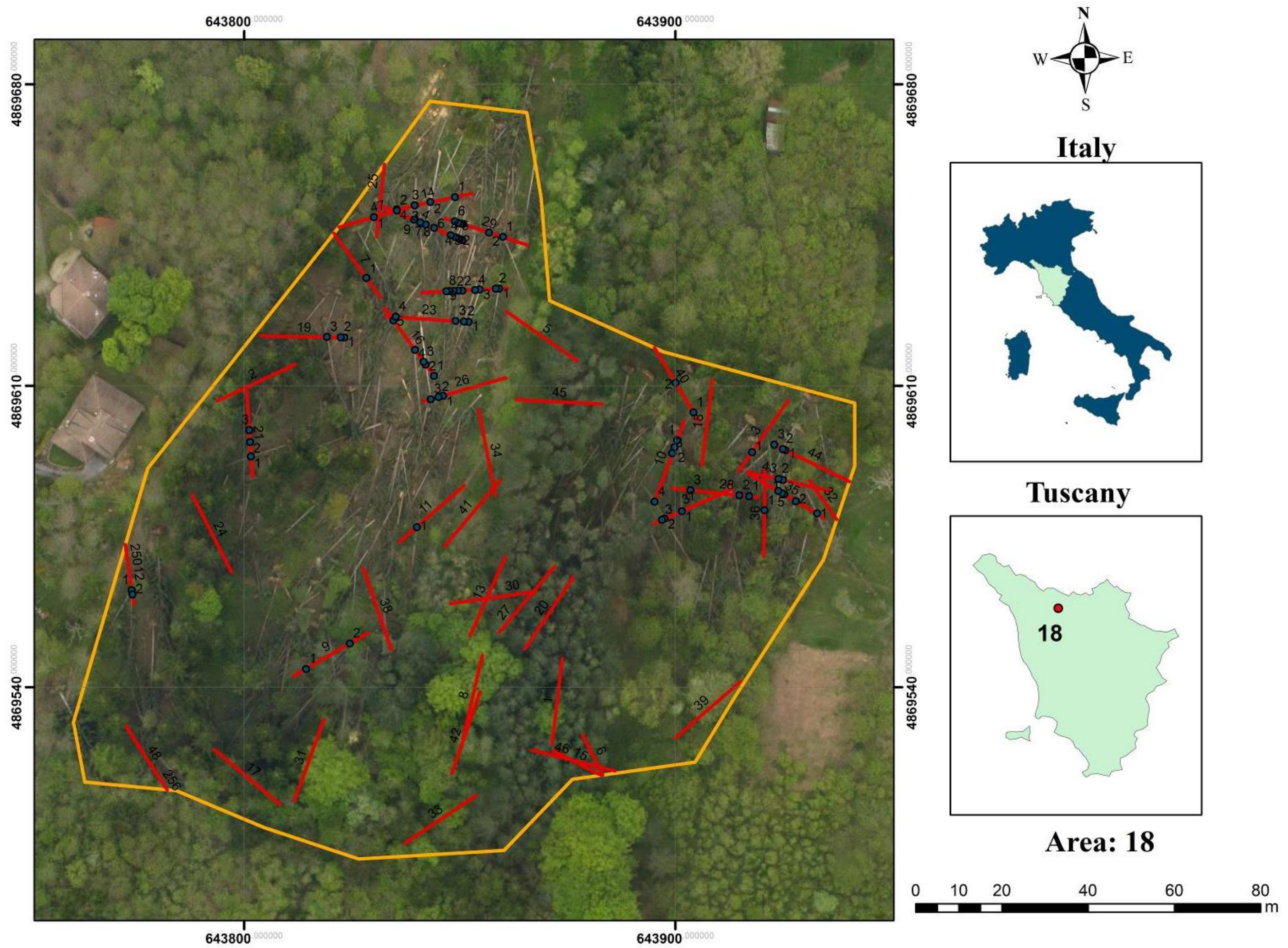
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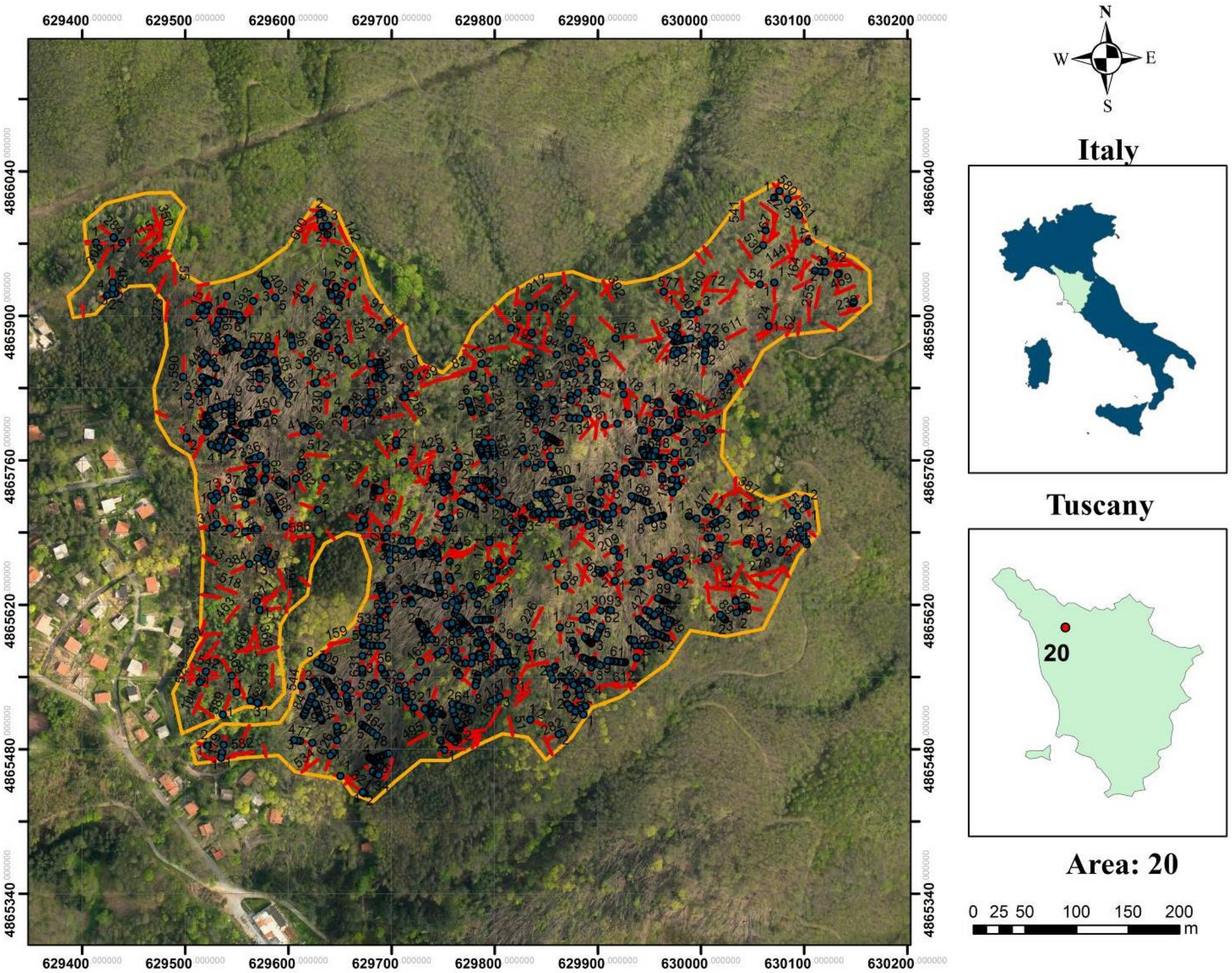
20
40
60
80
m



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W
E
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Tuscany
20
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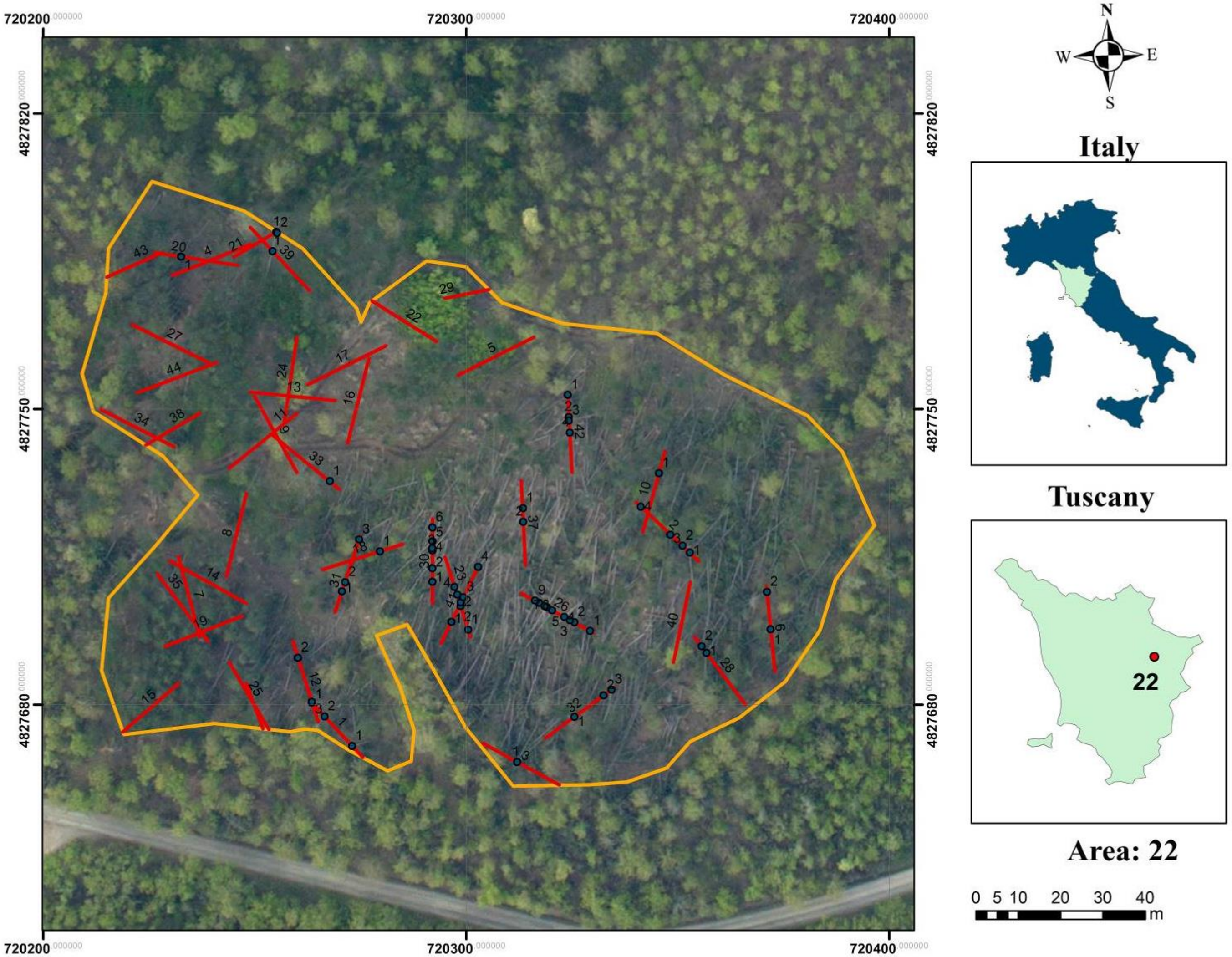
m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S
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Tuscany
22
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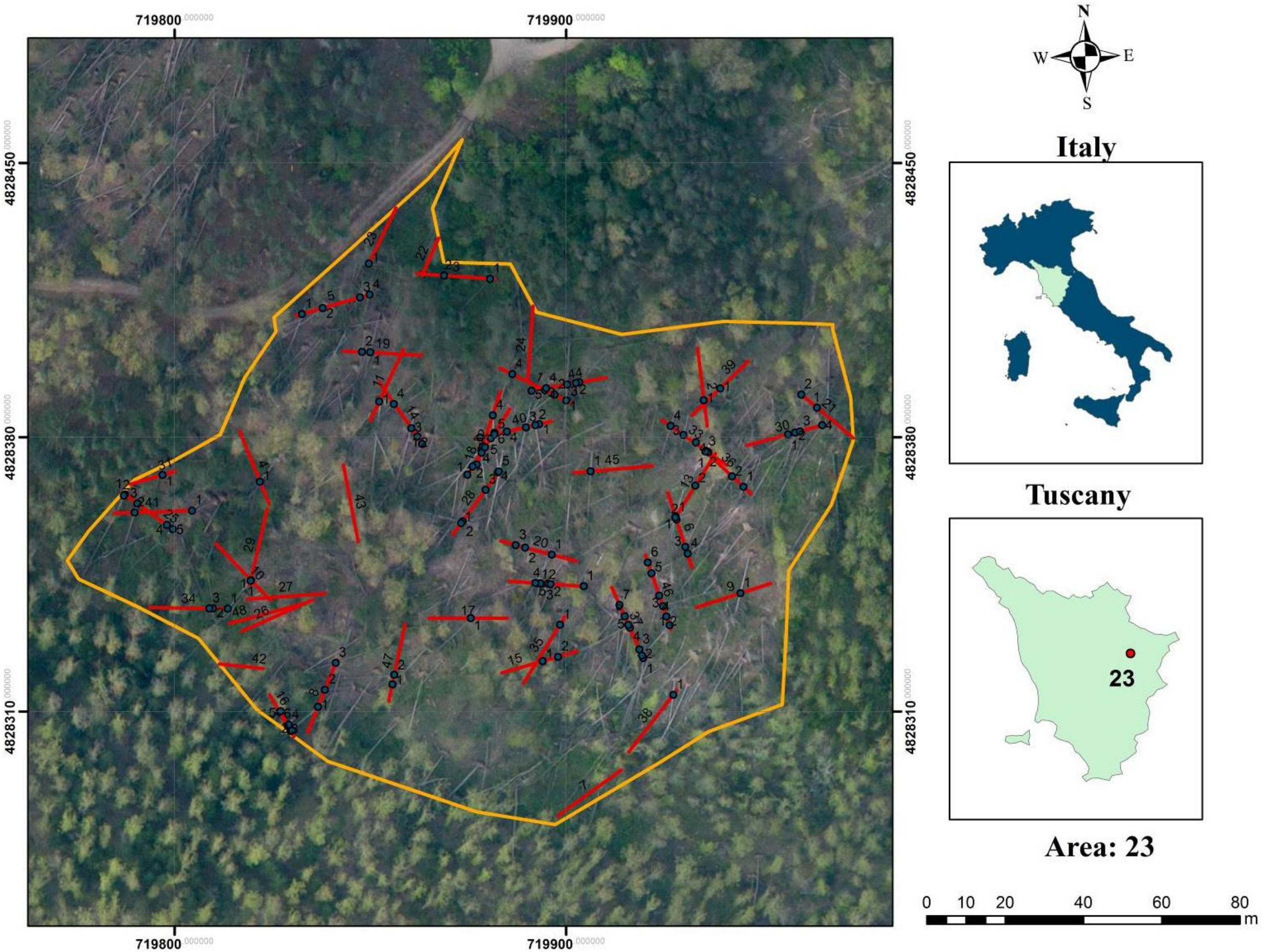
m



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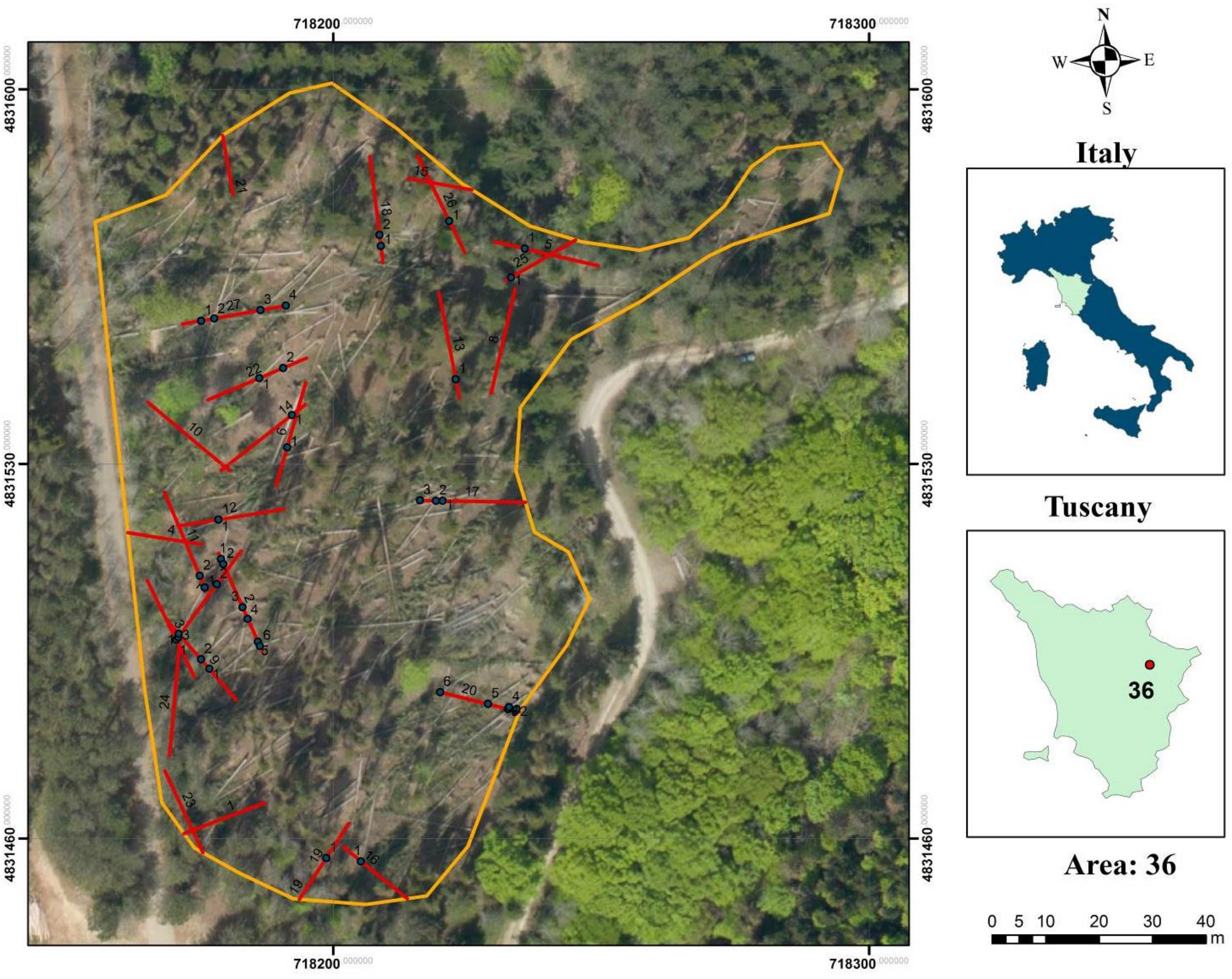
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