



The role of spatial data and geomatic approaches in treeline mapping: a review of methods and limitations

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Abstract

In the debate over global warming, treeline position is considered an important ecological indicator of climate change. Currently, analysis of upward treeline shift is often based on various spatial data processed by geomatic techniques. In this work, considering a selection of 31 reference papers, we assessed how the scientific community is using different methods to map treeline position and/or shifts using spatial datasets. We found that a significant number of published studies suffer from a low degree of awareness of processed data, which outcomes in potentially unreliable results that may compromise the validity of inference from the studies. Moreover, we propose an operational approach for easily incorporating consideration of spatial data quality, so as to improve reliability of results and better support ecological conclusions. Finally, we present a simulation of potential treeline vertical error for the Alpine region of Northern Italy, as driven by primary data quality.

Keywords: Treeline, optical remote sensing, data accuracy, vertical error, DTM.

Introduction

Treelines are ecotones particularly sensitive to alteration of temperature regimes and are considered significant indicators of climate [Korner, 2012] and land-use change [Motta et al., 2006; Bolli et al., 2007; Gehrig-Fasel et al., 2007].

There are several definitions of treeline and related terms [e.g. Kullman, 1979; Piussi and Schneider, 1985; Paulsen et al., 2000]. In most interpretations, treeline represents the upper altitudinal (or latitudinal) line connecting trees reaching a minimum height (usually between 2 and 5m) [Holtmeier, 2009]. Upper tree distribution boundaries are often fragmented and stretched over a transition ecotone and are variable in location, from few to hundreds of meters. Consequently, treeline position is not always objective and strongly dependent on the primary data used to map its location and, in particular, on the geometric resolution of the data [Camarero et al., 2000]. In the several last decades, spatial data and geomatic techniques have been increasingly adopted by ecologists for mapping studies, thanks to improved quality and open access. Nevertheless, these published works often report

incomplete information (lack of metadata) concerning primary data quality, generating potentially unreliable or at least questionable ecological results. Since treeline is always located in remote settings, spatial data and geomatic methods remain the best tools for its detection, arguing for an improved understanding of limitations, as well as approaches to strengthen applications.

For treeline mapping, there are several geomatics approaches that facilitate investigation of large sections of Earth's surface, especially when access is difficult for physical and/or political reasons [Troll, 1973; Kääb, 2005]. For instance, optical remote sensing techniques, in particular, are recognized as an essential tool for treeline ecotone observation, with specific focus on its position and dynamics. This is generally achieved by using bi-dimensional primary datasets such as satellite data [Driese, 1997; Milah et al., 2007; Bader, 2008; Zhang et al., 2009; Panigraphy et al., 2010], digital aerial orthoimages [Stueve et al., 2009; Ropas et al., 2012], and current and historical maps [Mast et al., 1997; Bryn, 2008], all managed by GIS (Geographic Information Systems) [Paulsen and Korner, 2001; Stueve et al., 2009]. Additionally, some basic terrain features (e.g. elevation, slope, aspect, etc.), that are useful to characterize treeline ecotones, can be easily obtained from different available DTMs (Digital Terrain Models) [Stueve et al., 2009; Kharuk, 2010; Groen, 2012]. Pixel-based [Tattoni et al., 2010] and object-oriented [Sitko et al., 2008] classification approaches, both supervised [Bader et al., 2008; Kral, 2009] and unsupervised [Klasner et al., 2002; Danby et al., 2007], of multispectral aerial and satellite imagery, are also used. Some studies base mapping on screen image-interpretation [Zhang et al., 2009]. Ground surveys, mainly performed by GNSS (Global Navigation Satellite Systems) [Groen et al., 2012; Ropars et al., 2012] are widely used to collect ground truth samples that are in turn used to train classifiers and validate classification results. Essentially, almost all subdisciplines of Geomatics can effectively support treeline detection. Geomatics is a transversal scientific discipline that requires specific skills, mainly related to uncertainty management; failure to consider uncertainty in the data can affect results reliability. Our study is specifically aimed at exploring if there are evident recurring limitations or methodological errors in published papers on treeline detection, by mean of spatial data and geomatics techniques, that may be limiting the reliability of the results. While our work focuses on treeline detection, our findings and conclusions may be applied to other works concerning different environmental studies (e.g. land use/land cover multitemporal works).

Specifically, our first objective was to statistically describe and measure recurrence of different data types and techniques from a selection of published papers on treeline mapping. Our second objective was to evaluate the extent that published papers reported the information needed to evaluate primary data quality with respect to measured treeline shifts; in other words, how often is reliability of mapping demonstrated. The latter objective was addressed by listing and formalizing the main sources of uncertainty related to treeline mapping and suggesting possible approaches to fill the gap. It is not our intention to present conclusions about reliability and significance of treeline shifts presented in the analyzed papers, but only to show how primary data quality should be taken into account and managed.

Consequently, we indicated those metadata that we retain absolutely needed (minimum requirements) in every work that relies on spatial primary data and geomatic approaches, and that are mandatory to prove that results are ecologically reliable.

Finally, we present a simulation of potential treeline vertical error, as affected by primary data quality, for a test area in the alpine region of Northern Italy.

Methods

We selected scientific papers for review using CAB direct and Scopus research databases spanning that last 35 years (1980-2015). We identified 80 papers using the following search keywords: “treeline position”, “treeline shifts”, “GIS”, “satellite data”, “aerial images”, “current maps”, “historical maps”, “LiDAR data”. Of the total, 31 papers were considered appropriate for the study since they used a geomatic approach and were focused on treeline applications to forestry. Works referring to other scientific fields like climate change, entomology, post-fire dynamics, CO₂ cycle, etc., where treeline plays a merely ecological role, with no focus on its spatial dynamics, were, in fact, excluded.

Table 1 reports the number of papers by scientific journal. Selected papers focused on both approaches to treeline position (9 works) and shift (22 works) mapping.

Table 1- Number of papers by scientific journal.

Scientific journals	Number of papers
Arctic, Antarctic, and Alpine Research	4
Current Science	1
Ecological Indicators	1
Ecological Modeling	1
Ecology	1
Erdkunde	1
Forest Ecology and Management	2
GIScience & Remote Sensing	1
Global Change Biology	1
Global Ecology and Biogeography	1
iForest - Biogeosciences and Forestry	1
International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences (Book, Volume XXXVIII-8/W20, 2011)	1
Journal of Biogeography	2
Journal of Mountain Science	1
Journal of Vegetation Science	4
Landscape Online	1
Mountain Research and Development	2
Norwegian Journal of Geography	1
Plant Biosystems	1
Plant Ecology & Diversity	1
Remote Sensing of Environment	1
Tropical Ecology	1

Our analysis proceeded along two directions. First, in an examination of “techniques and data analysis”, we explored how frequently each geomatic approach and spatial data type were used in selected papers. Second, we conducted an “accuracy analysis”, which was aimed at assessing if and how spatial datasets (maps and optical remotely sensed datasets) maintained consistency between data nominal accuracy and reference scale. In this case, *reference scale* is the one the authors of the papers intended for their work (if stated), which may have been different from the scale of the data they based their mapping on. Conversely, *nominal map scale* is the scale that primary data are suitable for, namely the scale related to geometric resolution or declared spatial accuracy. *Map uncertainty* (or accuracy) is the horizontal (or vertical) error (generally expressed in meters) that potentially affects digital maps or georeferenced images. Given these definitions, consistency of primary data nominal scale with the reference scale, is an important consideration when evaluating the degree of data awareness of authors.

Techniques and data analysis

Initially a classification and statistical analysis of geomatic approaches used in published studies (GNSS, GIS, optical remote sensing, digital photogrammetry and integrated approaches) was done. Secondly, the primary data types (satellite and aerial imagery, DTMs and digital maps) were considered and related statistics computed. Since vegetation mapping was a basic step for most studies, we also focused on classification methods used in the different papers. Finally, time trend of papers using geomatics approaches and spatial data for treeline mapping was explored.

Accuracy analysis

For this part of the study, we evaluated the perceived awareness of primary data accuracy in the published papers and how accuracy was managed in subsequent computations.

First, we investigated if and how metadata of spatial data were reported in the analyzed papers. Specifically, we looked for information about coordinate reference system name, geometric resolution (pixel size), nominal map scale. Additional information that we looked for was the reference scale the authors intended for their work. We also considered if, where present, geometric resolution was “*directly*” reported or if it was “*indirectly*” deductible from data type. Additionally, if both nominal map scale and reference scale were known, we tested their consistency; this is essential information needed to assess the suitability of datasets with respect to the reference scale of the study, i.e. reliability of results.

We also counted the papers that reported DTM vertical accuracy, either *directly* or *indirectly*. For indirect determination, accuracy was not explicitly reported in paper, but could be deduced if DTM source is known.

An additional assessment focused on recurrence of studies dealing with treeline mapping at a single time ($h[t_1]$) or in time (shifts, $\Delta h = h[t_2] - h[t_1]$).

Finally, we focused on vertical uncertainty of treeline mapping and developed an operational approach that can be easily adopted for its local estimation. Uncertainty depends on horizontal accuracy (σ_{xy}) of primary data used for treeline mapping, on slope, and on DTM vertical accuracy. DTM affects treeline position accuracy directly in the following ways: if treeline mapping is performed at a single time, and σ_{xy} is assumed as null, its vertical uncertainty can be retained equal to the one affecting DTM (σ_z), that strictly depends on

DTM type.

DTM can affect treeline vertical position accuracy *indirectly* through the effect of horizontal treeline mapping error (depending on primary data quality). It is known that in steep mountainous regions, a small horizontal shift results in a not negligible vertical shift. This effect can be modeled by Equation [1].

$$\varepsilon_z = \sigma_{xy} \cdot \tan(\nu) \quad [1]$$

where ε_z is the estimated height error related to slope effect, ν the local slope (degree), and σ_{xy} is the horizontal accuracy of the data used to map treeline position (satellite/aerial imagery or maps). In the best case scenario, ε_z can be assumed to be equal to the nominal horizontal accuracy of the image/map used to map treeline. As a result, local treeline vertical position uncertainty (σ_T) can be estimated according to Equation [2].

$$\sigma_T = \varepsilon_z + \sigma_z \quad [2]$$

If mapping involves treeline shift over time (Δh) then DTM error must be propagated along the difference, according to the Variance Propagation Law [Bevington and Robinson, 2002]. A first approximated estimation of shift uncertainty ($\sigma_{\Delta h}$) can be obtained as reported in Equation [3].

$$\sigma_{\Delta h} = \sqrt{2} \cdot \sigma_T \quad [3]$$

No treeline shift that is less than $\sigma_{\Delta h}$ can be considered significant. Shifts greater than $\sigma_{\Delta h}$ are considered reliable measures and must be reported as $\Delta h \pm \sigma_{\Delta h}$.

To further explore the importance of this type of error, we considered some of the mostly used DTMs, including satellite-derived, aerial-derived, LiDAR-derived data. For satellite-derived DTMs, we considered: a) SRTM (Shuttle Radar Topography Mission), having an absolute height accuracy = 16m; relative height accuracy = 10m (Jet propulsion Laboratory – California Institute of Technology – Nasa); geometric resolution = 1'' (about 90m) and b) ASTER GDEM (Advance Spaceborne Thermal Emission and Reflection Radiometer - Global Digital Elevation Map) having an absolute height accuracy = 20 meters at 95% confidence [ASTER GDEM Validation Team, ASTER Global DEM Validation Summary Report]; geometric resolution = 30m.

For DTMs obtained by aerial photogrammetry no general indications can be given as accuracy strictly depends on acquisition. If flight height (H), acquisition base (B), focal length (f) and sensor/film size and resolution are known, absolute height accuracy can be estimated through Equation [4] [Kraus, 1994]:

$$\sigma_z = \frac{H^2}{f \cdot B} \cdot \sigma_{\xi\eta} \quad [4]$$

where $\sigma_{\xi\eta}$ is generally assumed (in digital photogrammetry) equal to half a physical pixel size (μm) of sensor.

Lastly, DTMs generated by ALS (Aerial LiDAR System) are potentially the most accurate. Accuracy depends on flight height but generally we can assume a reference value $\sigma_z = 0.15\text{m}$ [Baltsavias, 1999].

For horizontal accuracy (σ_{xy}) standard values suggested by national mapping agencies can be used; ordinarily, accuracy is standardized in the map drawing domain (φ_{xy}) (Tab. 2).

In this way, the same φ_{xy} produces different accuracy values (σ_{xy}) depending on map scale (1: S), such that $\sigma_{xy} = \varphi_{xy} \cdot (S)$. In the Italian national context, $\varphi_{xy} = 0.200\text{ mm}$ [Gomasasca, 2004]. In the international context, the American Society of Photogrammetry and Remote Sensing (ASPRS) defines a horizontal accuracy standard (for large-scale maps) of 0.25 mm. Alternatively, ASPRS [1990] defines a CMAS (circular map accuracy standard) corresponding to 90% circular map error equal to 1/47th of an inch (0.54mm) at the scale of the map (Tab. 2).

Table 2 - Horizontal accuracy (σ_{xy}) and CMAS values for different nominal map scales, with reference to the international context.

Map scale 1:	σ_{xy} (m)	CMAS (m)
2,000	0.50	1.07
5,000	1.25	2.68
10,000	2.50	5.35
25,000	6.25	13.38
50,000	12.50	26.75
100,000	25.00	53.50
250,000	62.50	133.75
500,000	125.00	267.50
1,000,000	250.00	535.00

We modeled ε_z to demonstrate when it reaches non-negligible values, by considering the most common nominal map scales (1:1,000; 1:2,000; 1:10,000; 1:25,000; 1:50,000; 1:100,000; 1:1,000,000) and arbitrarily changing slope value. Resulting ε_z values were then compared with different DTMs vertical accuracies (ALS DTM, 0.15m; photogrammetric DTM, 5m; SRTM, 16m).

Finally, to further demonstrate the impact of DTMs *indirect* error (ε_z) in an operational context, we simulated the vertical error distribution for the entire alpine region of Northern Italy (about 51,900 km²). Vertical error was estimated by assuming that treeline mapping was achieved by interpreting primary spatial data having a 1:100,000 nominal map scale (Landsat TM imagery). Error classes were defined by considering vertical accuracy of ALS

DTMs ($\sigma_z = 0.15\text{m}$, error class $\sigma_z < 0.50\text{ m}$), photogrammetric DTMs ($\sigma_z = 5\text{ m}$, error class $5\text{ m} < \sigma_z < 16\text{m}$), and SRTM data ($\sigma_z = 16\text{m}$, error class $\sigma_z > 16\text{m}$).

Results

Techniques and data analysis

Statistics for published papers using spatial data and geomatic techniques for treeline mapping are summarized in Table 3. Note that the overall number of observations is higher than the total number of considered papers (31) because some studies included more than one spatial data type or geomatic technique. Analysis showed a recurrent integrated use of different data sources in 23 papers. The following data combinations were evident (Tab. 3): different satellite imagery types (9 papers); satellite and aerial images (4 papers), satellite images and digital maps (5 papers), and aerial images and digital maps (5 papers).

Table 3 - Geomatic techniques used for treeline mapping.

Geomatic techniques	N° of papers
GNSS	7
GIS	24
Integrated approach	23
Different satellite data types	9
Satellite data + aerial images	4
Satellite data + maps	5
Aerial images + maps	5
Digital photogrammetry	12

Specifically focusing on satellite images (13 papers), Landsat imagery was the most common source (9 papers) and among these, five papers refer to Thematic Mapper (TM) imagery, three to Enhanced Thematic Mapper (ETM+) imagery, and four to Multi Spectral Scanner (MSS) imagery. Linear Imaging Self Scanning Sensor (LISS III) data were used in two papers. Other satellite data were found one time each including Satellites Pour l'Observation de la Terre (SPOT), IKONOS-2, Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), QuickBird, LISS IV, Google Pro, Hexagon, Key Hole (KH-4B), Advance Land Observing Satellite (ALOS). Aerial LiDAR (ALS) data were used in two works.

DTM datasets were found in 25 papers. SRTM data resulted the most commonly used one (5 papers). ASTER GDEM was used in four papers; USGS DEM and DHM25 were used in one paper each; DTMs derived from ALS were used in two papers. Twelve papers used different not specified DTM types.

In treeline mapping, vegetation classification seems to be almost a mandatory step. In fact, majority of works dealt with image classification or interpretation based on different methods (Tab. 4). Specifically, both supervised and unsupervised classification methods (pixel-based and object-oriented) were used to map vegetation, basically exploiting spectral signatures obtained from imagery of multispectral sensors. Other techniques such as on

screen photo-interpretation and vegetation classes definition, were adopted in few papers. Finally, historical maps and ground data were recognized as the mostly used information sources for supporting and validating classification methods and results.

Table 4 - Vegetation classification methods and techniques for treeline mapping.

Vegetation classification	N° of papers
Yes	26
No	5
Classification approach (multispectral imagery)	
Supervised classifiers	9
Pixel-based	7
Object-oriented	2
Unsupervised classifiers	4
Other techniques	
On screen photo-interpretation	10
Vegetation classes	3
Historical maps	4
Ground survey	22

Lastly, Figure 1 shows the time trend of papers using spatial data and geomatic techniques for treeline mapping. A constant increase in the number of papers is evident from year 2008.

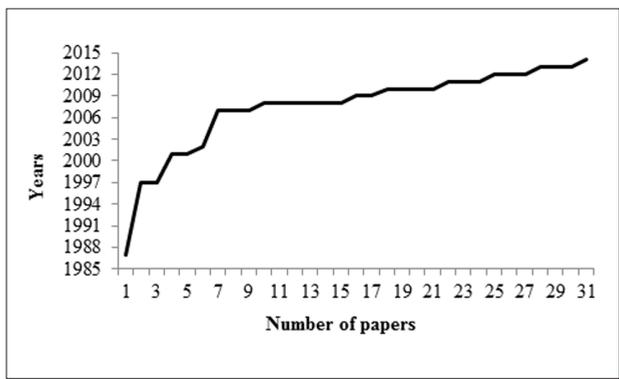


Figure 1 - Temporal trend of papers based on spatial data and geomatic approaches for treeline mapping.

Accuracy analysis

We found that the reference system was correctly defined only in eight papers; in these cases both projection (e.g. UTM zone 32) and Datum (e.g. WGS84) were reported. Conversely, 23 papers had incomplete information (commonly DATUM name is missing) (Tab. 5).

We found that only five papers explicitly reported the reference scale intended by authors for the study (Tab. 5). For those that did not report this, it was impossible to verify if spatial data quality was consistent with reference scale.

Table 5 - Statistics for parameters considered during the accuracy analysis.

Reference system	N° of papers
Correct declaration	8
Incomplete declaration	23
Reference Scale	
Declared	5
Undeclared	26
Aerial/satellite and maps horizontal accuracy	
Direct declaration	20
Indirect declaration	9
No declaration	2
DTMs vertical accuracy	
Direct declaration	1
Indirect declaration	12
No declaration	12
Treeline mapping	
Vertical Position ($h[t_1]$)	5
Vertical shift ($\Delta h = h[t_2] - h[t_1]$)	13
Other	4
GNSS survey accuracy	
Direct declaration	1
Indirect declaration (model type)	3
No declaration	3

For horizontal accuracy analysis, only 20 papers reported *direct* information (σ_{xy}). Nine studies included nominal scale of maps, permitting us to indirectly estimate horizontal accuracy. No information was given in two papers.

Twenty-five studies made use of a DTM for mapping treeline vertical position. Of these, 12 did not report DTM type, while 12 papers did not declared DTM vertical accuracy and, finally, only one reported DTM type and relative vertical accuracy.

Five papers dealt with treeline mapping at a single time ($h[t_1]$), while 13 considered treeline shift in time (Δh).

GNSSs positioning was used in seven papers; among these, only one directly reported survey accuracy, three reported instrument and survey type (from which accuracy can be deduced), while three reported no data.

According to the above mentioned criteria only eleven of the reviewed works measuring treeline position and shifts provided sufficient information about primary spatial data, and thus were able to demonstrate reliability of measurements. For the remaining papers nothing

can be said since σ_z and/or σ_{xy} were not reported.

The importance of ε_z was modeled and mapped using Equation [1]. The simulation was run using different values of σ_{xy} corresponding to different nominal map scales (1:1,000; 1:2,000; 1:10,000; 1:25,000; 1:50,000; 1:100,000; 1:1,000,000) and based on international standards. To point out the influence of satellite imagery GSD (Ground Sample Distance) on final vertical accuracy, we report (Fig. 2) the name of some well known satellite missions (that can be easily related to a correspondent map scale). Red and blue horizontal lines define the photogrammetric ($\sigma_z=5\text{m}$) and SRTM ($\sigma_z=16\text{m}$) DTMs vertical accuracy, respectively.

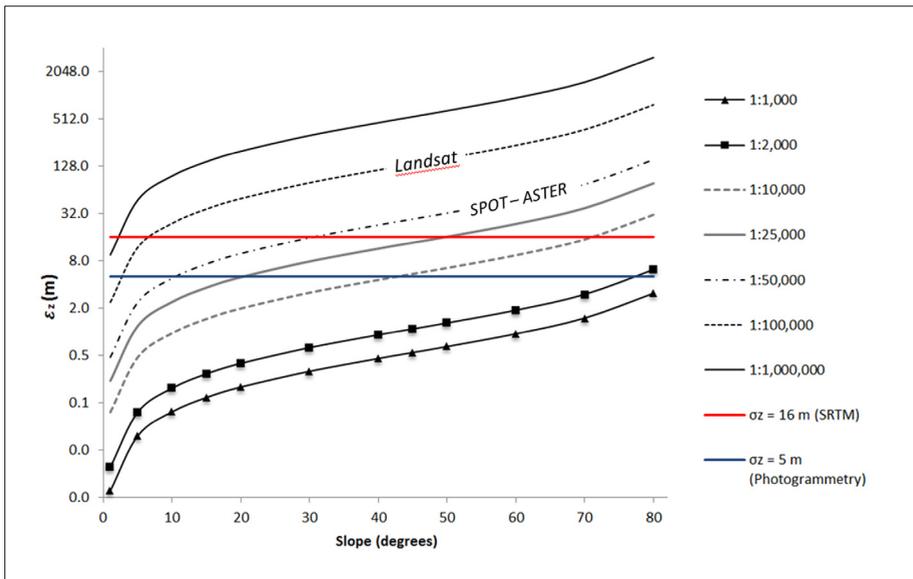


Figure 2 - Vertical error resulting from the combined effect of terrain slope and horizontal accuracy (theoretical) of data used for treeline mapping. Different nominal map scale values are considered; the red line represents SRTM DTM accuracy ($\sigma_z=16\text{m}$); the blue line represents a typical value of accuracy for a DTM obtained through aerial photogrammetry ($\sigma_z=5\text{m}$). Y axis is logarithmic (base 2).

For areas having slope angles higher than 8-10 degrees, the vertical error caused by slope tends to be significant respect to the adopted DTM accuracy ($\varepsilon_z > \sigma_z$). For DTM having higher accuracy (e.g. ALS DTMs), lower slope angles have to be considered.

A test site was then selected to model ε_z and to explore where it is significant in a real landscape. The test area used was the northern Italy, where the Alps can be assumed as representative of an extreme mountainous context where treeline can be mapped. In the test area, height values ranged between 0 and about 4800m a.s.l. A map of ε_z related to a 1:100,000 nominal map scale, was generated using SRTM DTM (Fig. 3). Error classes were defined according to the used data sources: ALS DTM ($\sigma_z < 0.5\text{m}$), photogrammetric DTM ($5\text{m} < \sigma_z < 16\text{m}$), and satellite SRTM ($\sigma_z > 16\text{m}$).

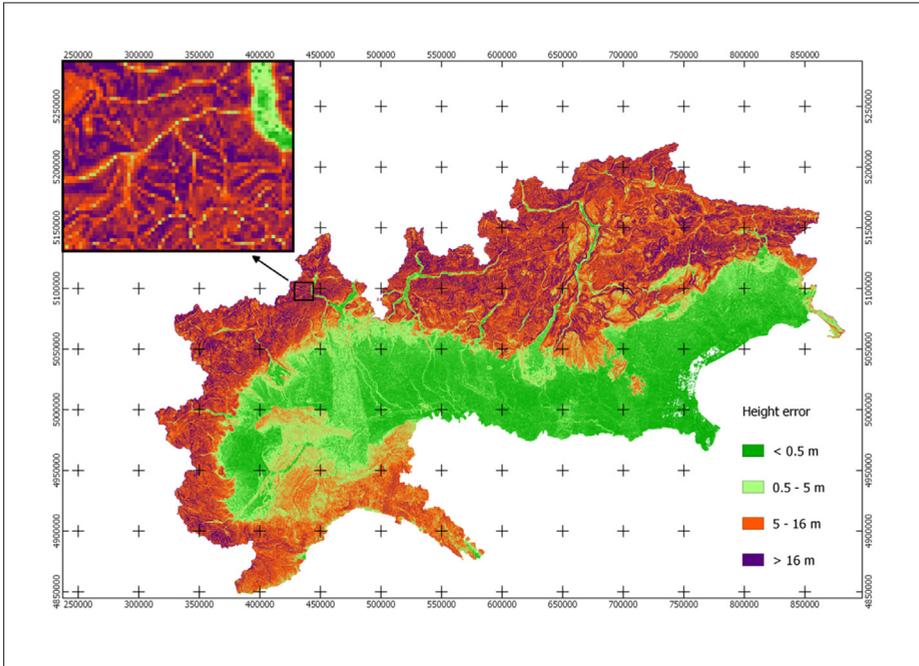


Figure 3 - Map of the vertical error contribution related to horizontal uncertainty of primary data used to map treeline position. The simulation used to produce the map considered a horizontal accuracy of 25m corresponding to a nominal map scale of 1:100,000. Total local vertical error (potential) can be obtained summing this contribution to that of the DTM used for treeline height measurement (not considered in the simulation).

The cumulative histogram of ε_z occurring in the height range 1500-2500m a.s.l., was calculated (Fig. 4).

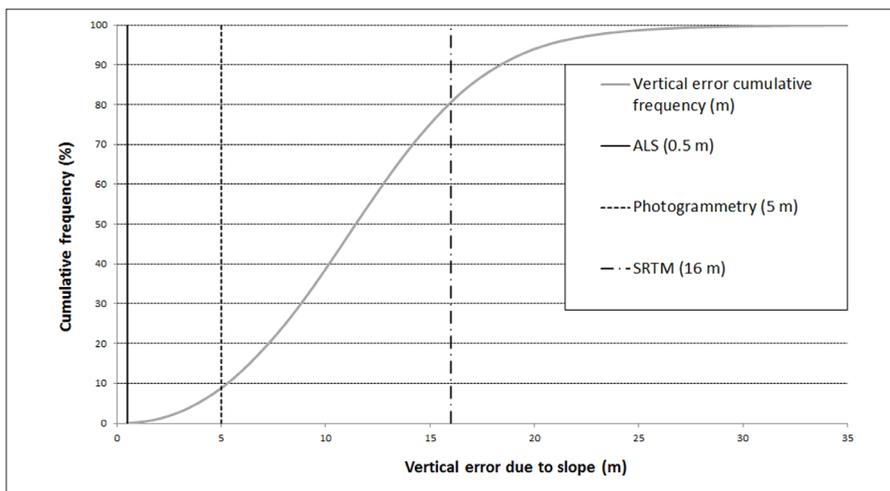


Figure 4 - Cumulative frequency of vertical error (related to the above simulation) affecting areas located in the height range 1500-2500m a.s.l., where treeline generally is found.

According to the simulation, if Landsat imagery (compliant with a 1:100,000 nominal scale map) is used in combination with SRTM DTM, in about the 20.0% of the area a significant ε_z value can be observed.

Discussion

Our results showed that spatial data and geomatic techniques are essential in mapping treeline ecotones spatial dynamics. Particularly, we showed which spatial data and techniques are most frequently used for treeline detection. Moreover, we pointed out gaps in data processing, mainly as related to uncertainty. Our work underscored a generally poor awareness about the effect of primary spatial data quality on uncertainty of final measurements.

We found some “weaknesses” affecting various studies. Concerning the use of GNSS technology (Tab. 5), specifications about survey strategy and accuracy, and instrument type were often incomplete.

Regarding primary spatial data used to map treeline, horizontal accuracy information was generally missing or incomplete. Moreover, data reference system specification was often lacking (e.g. UTM system is reported without specifying the Zone, and the name of the datum or projection is sometimes used in place of reference system). When dealing with data from different sources, a correct definition of reference systems used guarantees that interacting data are spatially coherent. This ensures that further degradation of horizontal uncertainty of treeline position does not occur. For example, when looking at the Italian national context it is quite common to find studies (especially working at a regional scale where differences are not so evident) in which the UTM 32 N ED50 reference frame is confused with the UTM 32 N WGS84. This confusion generates a ground displacement between the two systems of about 220m.

Additionally, it is common that the geometric resolution of images or DTMs are not reported, making the evaluation of measures reliability impossible.

In the same way, nominal map scale and related horizontal accuracy were not reported in some papers. As such, no evaluation of the consistency of the processed data with respect to the expected reference scale is possible. Doing this is the starting point to carry out correct mapping [Boccardo et al., 2003] including mapping of treeline ecotones.

A further critical point of concern involves DTM use. This type of geographical data can directly and indirectly affect final results [Boccardo et al., 2005]. Direct effects are related to the internal accuracy of the DTM. Indirect effects relate to error propagation generated by combining horizontal error of treeline position (depending on the image or map used to interpret/classify it) with terrain slope. Slope value is a key factor in treeline mapping since treeline location generally occurs in regions with steep slope. The effect of slope value on treeline determination is not negligible, as we have demonstrated, especially when using medium resolution/scale primary spatial data (Fig. 2).

Another DTM indirect effect that can further degrade treeline horizontal position is relief displacement affecting objects overlaying terrain. The simplified approach we presented above, actually, neglects this effect that generally occurs during aerial or satellite orthoimages interpretation/classification. In fact, digital orthoimages are mainly generated using DTMs and not DSMs (Digital Surface Models); this determines that the top of rising objects standing over the earth's surface (trees, houses, etc.) are shifted respect to their

real position. Shift depends on object height, terrain shape and geometry of acquisition. Ordinary orthoprojection processing does not remove this discrepancy. In other words, the joint effect of acquisition geometry with terrain slope generates a further non negligible uncertainty factor in treeline mapping, that normally relies on tree canopy detection, that, for this reason, is horizontally displaced from its real position. At the moment, authors are modeling this effect, that, anyway, was not taken into account in this work.

An additional source of uncertainty, not addressed in this study, is related to the use of historical maps (some going back to 1850) that may be used as references to compare to current treeline position. Since historical maps typically carry a higher degree of inaccuracy and uncertainty when compared to contemporary cartographic databases [Tucci and Giordano, 2011], shifts measured through such as comparison necessarily suffer from an intrinsic higher uncertainty related to the nature of the historical map itself; in fact, older maps were drawn using old techniques and, in many cases, on the basis of approximated surveys, especially in those areas of difficult access. Moreover, all ancient/old maps are originally paper drawings that are then digitized and georeferenced. Both paper maps and scanning systems used for digitization, introduce many further deformations on the final digital map; often these cannot be removed or minimized by the georeferencing in a GIS. Accordingly, the final map will include a very low degree of metric reliability.

Methodologies based on human visual interpretation suffer problems related to subjectivity. There is no way to specify an “a-priori estimation” of the potential uncertainty of mapping. Additionally, it is evident that treeline position obtained by photos (or maps) through on-screen interpretation can only be horizontally defined. To get height information, the result has to be compared with a height data source (DTM). From this point on, uncertainty follows the same path as the one previously mentioned.

Conclusions

This study shows that spatial data and geomatic techniques are powerful tools for ecological studies focused on treeline position and shift mapping. We point out that appropriate ecological results are dependent on spatial data management, but their reliability relies on the way metadata are interpreted and reported. Every measurement has to be qualified and we propose an operational approach to do this easily as applied to treeline position vertical accuracy. Considering that reliable ecological results are dependent on correct management of spatial data and metadata, we suggest the following minimum requirements for every study that use them:

- a) the coordinate reference system has to be rigorously defined in terms of datum, projection type, zone (eventually) for all spatial data;
- b) geometric resolution of images, raster digital maps, and DTM has to be explicitly reported; if maps are supplied in a vector format the nominal map scale needs to be reported. However, direct reporting of vertical and horizontal accuracy of data is always better;
- c) consistency of primary spatial data scale with respect to reference scale of the study has to be demonstrated by comparing theoretical accuracy of reference scale with the one potentially affecting primary spatial data; this has to be managed along the workflow, taking care to be aware of eventual error propagation;
- d) if optical multispectral satellite/aerial imagery are used, all information about spectral and radiometric features of the available bands needs to be clearly stated;

- e) if scanned aerial images (or native digital ones) are used, the following minimal information has to be supplied: airplane flight height, camera focal length, base of the acquisition (if stereo-pairs are considered), sensor/film size and, for scanned paper prints, scan quality information (dots per inch, dpi);
- f) if GNSS technology is used, receiver model type needs to be reported, together with survey accuracy and differential correction strategy (if involved);
- g) every final measurement should have a reported value and related uncertainty to make eventual users aware of limitations about the information.

We believe that taking into consideration these minimum requirements can minimize uncertainty of results while maximizing reliability of spatial measurements. While our review focused on treeline studies, similar considerations can be applied to other studies and applications where digital spatial data are used.

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