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A novel approach for measuring treeline spatial complexity

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Abstract. Treelines, defined as *ecotonal zones between closed forest and the uppermost trees*, are particularly sensitive to global changes related to climate and anthropic activities. Different mechanisms of treeline formation can be detected as subtle differences in ecotonal structure, which in turn have important implications for how treelines function and potentially respond to global changes. So, it is of interest to be able to measure in a precise and quantitative way treelines' properties reflecting climate and land use changes. Classical tools adopted to measure treeline spatial patterns are not able to fully understand the limiting factors affecting them. This work presents a novel textural analysis of treeline spatial structure based on the measurement of surface roughness, and applies the corresponding metrics to twenty study areas at both Upper and Lower treelines, where all tree crowns have been mapped at high precision. Preliminary results are promising and motivate future and more extensive evaluations on bigger datasets.

1. Introduction

Treelines are transition zones whose position is widely thought to be temperature sensitive, and potentially responsive to climate warming [1]. For this reason, the dynamics of treelines are studied around the globe with the aim of detecting changes, understanding responses to temperature variation, and evaluating the threats to alpine and arctic biota in response to treeline movement, in high altitude and latitude communities [2]. At a landscape and local scales, treeline position, form (spatial pattern), and dynamics depend on multiple interactions of influencing factors and mechanisms [3], including human activities.

In some regions of the world, the altitudinal limit of the forest also called altitudinal treeline may be above (Upper treeline) or below (Lower treeline) the closed canopy forest. It is assumed that Upper and Lower treelines, like those shown in Figure 1, are conditioned by two different limiting factors: temperature and humidity, respectively [4]. The appearance of treelines, i.e. their spatial pattern, seems to be characterized by grouped trees or microsites in the case of

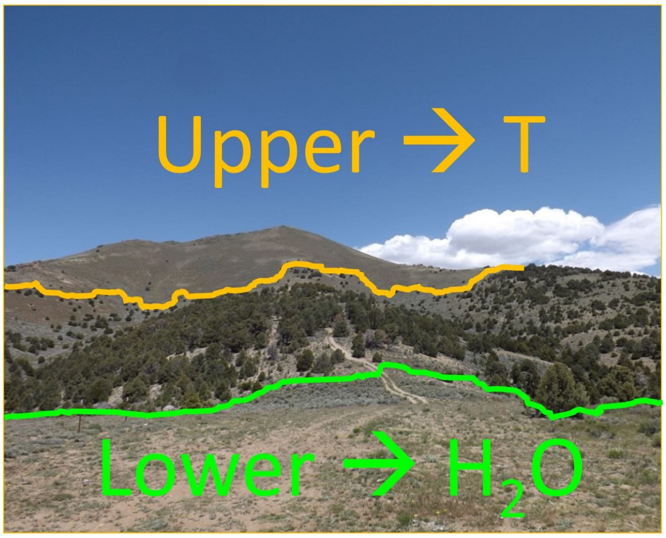


Figure 1. A visual example of Upper and Lower treelines, mostly affected by temperature (T) and water availability (H_2O), respectively.

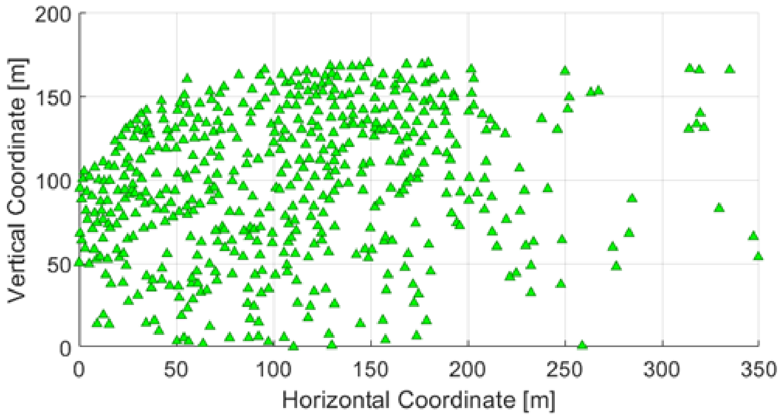
Upper treelines, whereas it is influenced by water availability or random effects in the Lower treelines. As a result, treelines' pattern is typically linear or at least regular in the Lower case, whereas it appears to be complex and spread in the Upper case.

In order to objectively analyze the dynamics of treelines, like changes in their shape and pattern over time, it is important to adopt a methodology based on clearly defined parameters, that can be quantitatively measured and compared. Given the fact that, at the authors' best knowledge, such a methodology has not been presented up to now, in this paper we propose to apply typical approach and parameters used in the domain of surface roughness measurements, to the characterization of treelines features and properties. The reference standard in Geometrical Product Specifications (GPS), the ISO 4287:1997 one, that was confirmed in 2015 [5], prescribes the profile method for surface texture characterization, and provides terms, definitions and surface texture parameters. We refer to this standard in order to identify the metrics that can be reasonably applied to characterize treelines.

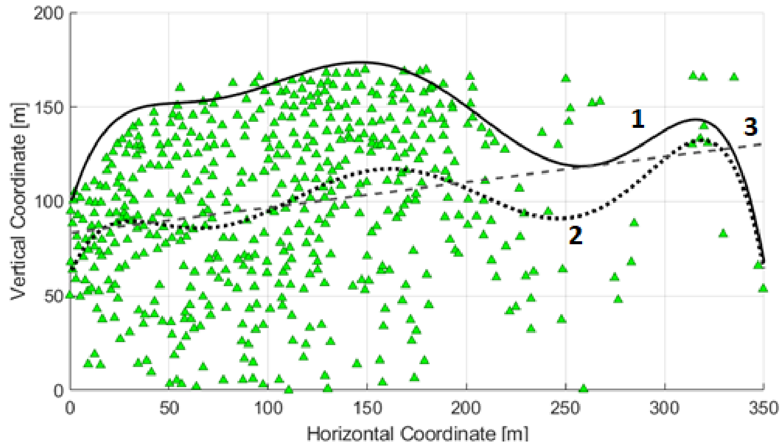
The paper is organized as follows: Section 2 introduces the metrics used in surface roughness measurements, and specifies how we applied them to treelines' data. Section 3 describes the experiments performed and discusses the results obtained. Finally, Section 4 draws the main conclusions of this work and highlights future developments.

2. Surface Roughness Metrics and Their Application to Treelines

The application of surface roughness measurements to treelines is possible because, in practice, measured surface texture data is not continuous but takes discrete values, similarly to the nature of the treeline data we have to process. In fact, treelines are given in the form of sets of points, each one corresponding to the position of a tree in a 2D view of a geographic area, representing a mountain slope. Each point is identified by its horizontal and vertical coordinates (x,y), within a common reference system. Figure 2(a) shows a graphical representation of a generic set of treeline data: each point in the graph identifies a tree. Figure 2(b) shows the same set of data, over which three trend curves have been fitted. Curve labelled as no. 1 corresponds to a degree-6 polynomial fitting the highest vertical coordinates of trees falling within the same 5 m - wide interval along the horizontal axis, whereas curve no. 2, that is very similar, shows a degree-6



(a)



(b)

Figure 2. Graphical representation of a generic set of treeline data: (a) trees' coordinates, (b) trend curves.

polynomial fitting the single trees' vertical coordinates. Finally, curve no. 3 is the set regression line, fitted by the method of least squares.

All the three curves in Figure 2(b) are obtained by interpolating the available trees' coordinates; however, this gives rise to synthetic values that do not correspond to actual trees in the observed area. In order to avoid the need of generating interpolated values, we apply the following surface texture parameters, that can be computed over discrete data:

- Average Line (AL), the dashed one in Figure 2(b): it is the line fitted by the method of least squares, computed over the primary roughness profile points. In its definition, the AL corresponds to the previously discussed curve no. 3 in Figure 2(b);
- R_a: it is the most commonly used and recognized parameter to evaluate a surface roughness profile, i.e. the arithmetic average absolute distance of the roughness profile points from the AL:

$$R_a = \frac{1}{l} \sum_{i=1}^{N} |d_i| \tag{1}$$

where l is the length of the AL, N is the number of points in the profile, and d_i is the Euclidean distance of each point from the AL, identified by the sample dashed arrows shown

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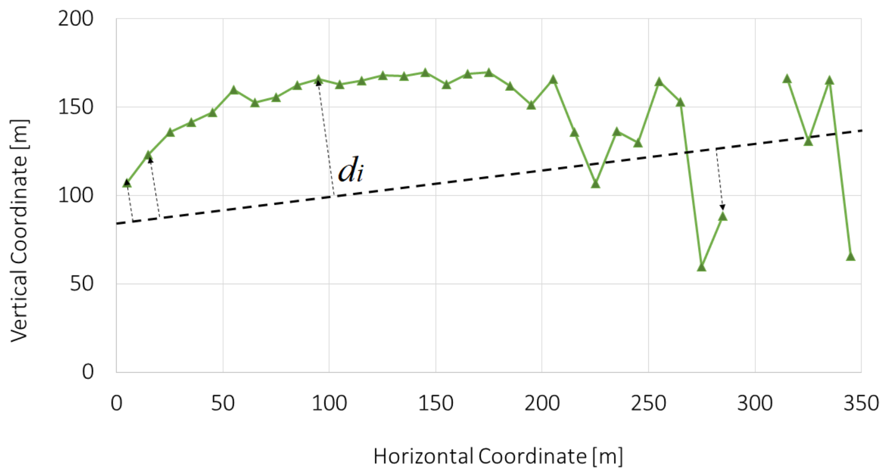

Figure 3. Graphical representation of R_a computation from trees' coordinates.

in Figure 3. The last one shows the line extracted from the trees' coordinates shown in Figure 2(a) by taking the highest tree in vertical coordinate every 5 m along the horizontal direction (x-axis). This line could be called "tree species line" using the ecological meaning of a line passing through the trees that live at the top of the slope;

- R_q: it is the RMS corresponding to R_a:

$$R_q = \sqrt{\frac{1}{l}\sum_{i=1}^{N} d_i^2} \tag{2}$$

- R_{sk} (skewness): it measures the symmetry of the roughness profile with respect to the AL, and can be used to highlight the different symmetry of roughness profiles exhibiting similar R_a and R_q:

$$R_{sk} = \frac{1}{R_q^3}\left[\frac{1}{l}\sum_{i=1}^{N} d_i^3\right] \tag{3}$$

- R_{ku} (kurtosis): it measures the profile acuity:

$$R_{ku} = \frac{1}{R_q^4}\left[\frac{1}{l}\sum_{i=1}^{N} d_i^4\right] \tag{4}$$

Additionally, parameters R_v^*, R_p^*, and R_t are considered, providing, respectively: the maximum distance from the AL of the profile point located under it; the maximum distance from the AL of the profile point located over it; and the corresponding distance between these two points.

3. Experiments and Results

Table 1. Roughness parameters evaluated over 10 UP treelines, with average (AVG) values in the last line.

Treeline	R_a	$R_q[m^{-1}]$	$R_{v^*}[m]$	$R_{p^*}[m]$	$R_t[m]$	$R_{sk}[m^{-1}]$	$R_{ku}[m^{-2}]$
UP1	37.04	44.86	96.26	82.66	178.92	-0.50	2.42
UP2	55.94	60.16	75.04	100.26	175.30	0.06	1.37
UP3	35.51	43.32	87.00	51.96	138.96	-0.90	2.38
UP4	26.94	34.45	78.01	77.40	155.41	0.05	2.77
UP5	32.04	38.14	69.38	81.19	150.57	0.07	2.26
UP6	26.34	31.67	83.03	51.39	134.43	-0.43	2.28
UP7	24.70	31.95	87.84	57.34	145.18	-0.80	3.53
UP8	33.36	38.71	70.14	68.46	138.60	0.02	1.87
UP9	52.00	56.76	106.00	68.38	174.39	-0.42	1.57
UP10	21.25	27.14	95.92	47.69	143.61	-0.79	4.33
AVG	34.51	40.72	84.86	68.67	153.54	-0.36	2.48

Table 2. Roughness parameters evaluated over 10 LOW treelines, with average (AVG) values in the last line.

Treeline	R_a	$R_q[m^{-1}]$	$R_{v^*}[m]$	$R_{p^*}[m]$	$R_t[m]$	$R_{sk}[m^{-1}]$	$R_{ku}[m^{-2}]$
LOW1	30.31	35.36	87.83	47.76	135.6	-0.65	2.41
LOW2	14.54	17.84	36.19	44.67	80.87	0.01	2.75
LOW3	30.33	37.55	47.81	99.23	147.04	0.89	2.85
LOW4	34.78	42.98	96.57	77.42	173.98	-0.59	2.61
LOW5	35.81	42.74	106.53	65.80	172.32	-0.46	2.65
LOW6	32.93	39.47	74.45	78.91	153.36	0.39	2.17
LOW7	24.11	30.19	107.97	50.16	158.13	-0.75	4.05
LOW8	26.02	31.61	70.89	55.00	125.89	-0.29	2.26
LOW9	41.21	48.20	102.17	66.73	168.89	-0.59	2.14
LOW10	40.01	48.18	119.35	59.68	179.03	-0.6	2.31
AVG	31.00	37.41	84.98	64.54	149.51	-0.26	2.62

The roughness parameters introduced in the previous section have been computed on 10 datasets representing transect plots of mapped trees (named UP1 to UP10) describing the Upper treeline, that is basically influenced by temperature variations, and on other 10 datasets (named LOW1 to LOW10) providing the Lower treeline, that is usually affected by water availability.

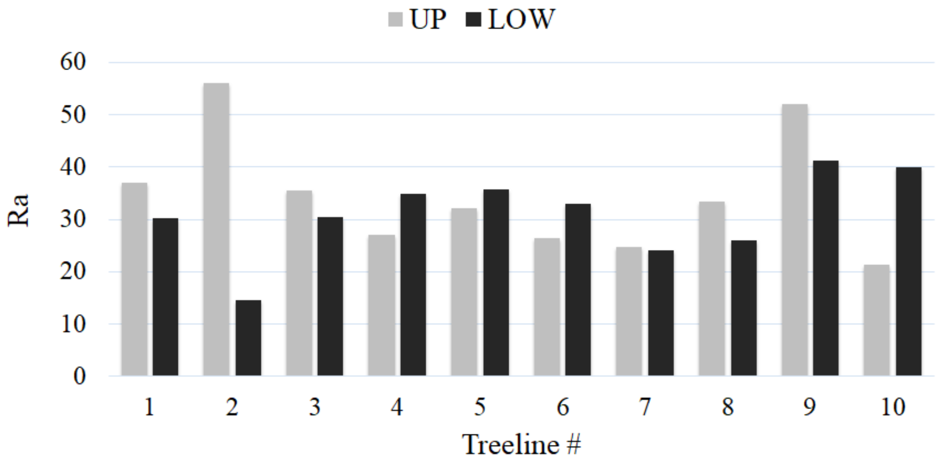

Figure 4. Graphical comparison of roughness parameter (R_a) values for each UP and LOW treeline.

Tables 1 and 2 report the resulting parameters' values for each treeline, and the average values computed over the 10 UP and LOW treelines, respectively.

Figure 4 compares the R_a parameter only, measured over both the 10 UP and LOW treelines. In six out of ten cases the UP datasets show greater values of the roughness parameter, than the corresponding LOW datasets. This observation is in line with the assumption that upper treelines are usually more irregular because less affected by anthropic interventions, than lower treelines that usually exhibit a more regular behavior. Figure 5 provides a graphical comparison of the average values of each surface texture parameter introduced in Section 2, computed over all the UP and LOW treelines. Again, it is possible to notice the prevalence of higher values for the parameters averaged over the available UP treelines. These preliminary results motivate the interest in applying the tools designed for surface texture measurement to the quantitative evaluation of treeline patterns too.

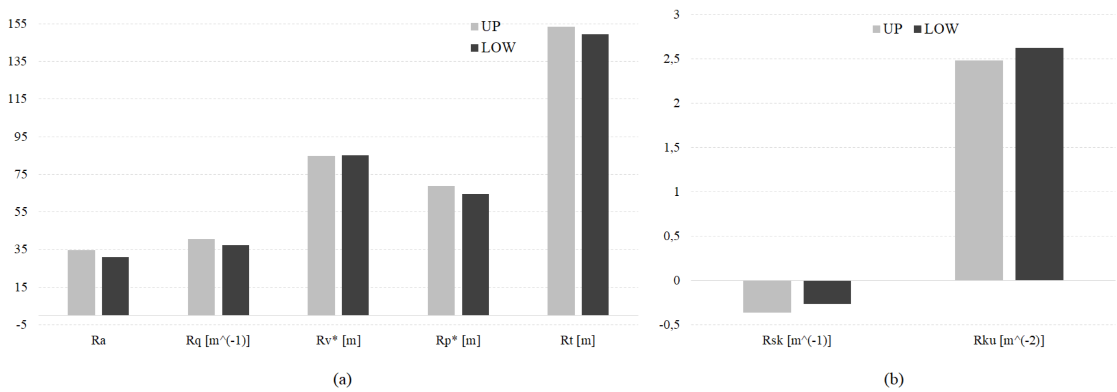

Figure 5. Graphical comparison of average roughness parameters values for all UP and LOW treelines: (a) R_a, R_q, R_v^*, R_p^*, R_t, (b) R_{sk} and R_{ku}.

4. Conclusion

With the purpose of describing the irregularity of Upper and Lower treelines, this paper proposes a metric based on the analogy to the measurement of surface roughness. Therefore, instead of using interpolated lines, we choose to use the extreme (maxima or minima) points measured; this eliminates all spatial filtering effects caused by interpolation algorithms. Among the available roughness measurements, the R_a one seems more suitable than others to catch and represent the different characteristics of Upper and Lower treelines. However, to reinforce this preliminary conclusion, a more significant evaluation of the R_a parameter requires to extend the analysis to a bigger amount of datasets.

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