A Word from Alpine Tundra: Watch Out, Forests Are Invading! – Spatial Detection of Alpine Treeline Ecotones in the Western United States

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Abstract

Human-mediated climate change over the past century has made significant impacts on global ecosystems and biodiversity including accelerating redistribution of the geographic ranges of species. In mountainous regions, the transition zone from continuous closed-canopy subalpine forests to treeless alpine tundra areas at higher elevations is commonly referred to as 'Alpine Treeline Ecotone' (ATE). Globally, warming climate is expected to drive the ATE upslope, which could lead to negative impacts on local biodiversity and modify ecosystem function. However, existing studies rely primarily on field-based data which are difficult and time consuming to collect. In this research, we define three critical characteristics of the ATE including 1) an abrupt spatial shift in vegetative activity as elevation varies, 2) reduction in vegetative activity as elevation increases, and 3) vegetative activity is at an intermediate level. Using the geospatial tools provided by Google Earth Engine, we construct an index (ATEI) to identify areas with the three ATE features based on the image gradients of vegetative activity and elevation datasets. Based on the ATEI and Google Earth imagery in 115 Landsat pixels, we establish a Logistic regression model to estimate the probability of whether or not a sampled pixel is located within the ATE. The prediction accuracy is approximately 80%. Furthermore, the ATEI-estimated ATE elevation is strongly correlated (r = 0.96) with a set of field-based data at 20 sampling sites from across the region. Based on the average annual ATEIs from 2009 to 2011, we estimate the average ATE elevation for each mountain range in the western U.S. The result varies from 1,183 m to 3,584 m. The detection metric developed in this study facilitates monitoring the geographic location and potential shifts of ATEs as well as the general impact of climate change in mountainous regions during recent decades. We also expect this approach to be useful in monitoring other ecosystem boundaries.

A Word from Alpine Tundra: Watch Out, Forests Are Invading!

Spatial Detection of Alpine Treeline Ecotones in the Western United States

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Introduction

Alpine Treeline Ecotone (ATE) refers to an ***abrupt transition zone*** from places where trees can survive (***subalpine forests***) to places where trees can NOT survive (***alpine tundra***) in global mountain environments.

ATE is very important because: 1) it's an ***important habitat*** for numerous species including trees, understory plants, birds, and mammals, and 2) it's relevant to many ***ecological functions*** such as carbon sequestration, nutrient and water cycling, snow retention, albedo and surface roughness, maintenance of biodiversity, etc.

ATE has an unique role under climate change, which is both a potential ***at-risk area*** and a powerful ***indicator***[7]. The warming climate is expected to drive the ATE upslope worldwide with some serious ecological consequences.

Data Pre-processing

The study domain (see light blue areas in *Fig. 1*) was determined by generating a 3-km buffer of the ***climatically estimated ATE***[4,8] in each mountain range[5,6] in the western U.S.

Based on the Landsat 5 imagery from 2009 to 2011[10], we calculated ***annual maximum NDVIs*** (Normalized Difference Vegetation Indices) at each pixel in the study domain.

Pre-detection sampling: 200 Landsat pixels were randomly selected within the study domain (see red dots in *Fig. 1*) and then were analyzed based on high-resolution imagery from 2009 to 2011 in Google Earth[1,9]. Their annual maximum NDVIs were used to construct an index for detecting ATEs (*Table 1*).

Index Construction

Based on the image gradients of NDVI and elevation[2] data, an ATE Index (ATEI) was constructed to identify areas with the following three key characteristics (*Table 1*).

1) ***Sharp gradient in vegetation:*** Abrupt spatial shift in vegetative activity as elevation varied.
2) ***Intermediate vegetation:*** Vegetative activity was at an intermediate level.
3) ***Opposite gradient directions:*** Reduction in vegetative activity as elevation increased.

Validation-pixel sampling: We sampled 300 Landsat pixels (see blue dots in Fig. 1) and classified them into two groups (out of/within the ATE) based the Google Earth imagery[1,9], which could be easily differentiated from each other through the ATEI metric (*Fig. 2*).

Detection Results

Using the ATEI to calculate the weighted-average elevation, the ***ATE elevation*** was estimated for each mountain range in the western U.S., which varied from 1,183 m to 3,584 m (see color of each polygon in *Fig. 1*). The ATEI-estimated elevation was strongly correlated (see *Fig. 3*, r = 0.96) with a set of ***field-based data***[11] at 20 sampling sites (see yellow dots in Fig. 1). Also, ***visual inspection*** confirmed that the potential ATE regions were detected very well in two significantly different mountain-range examples (see *Fig. 4*).

Acknowledgements

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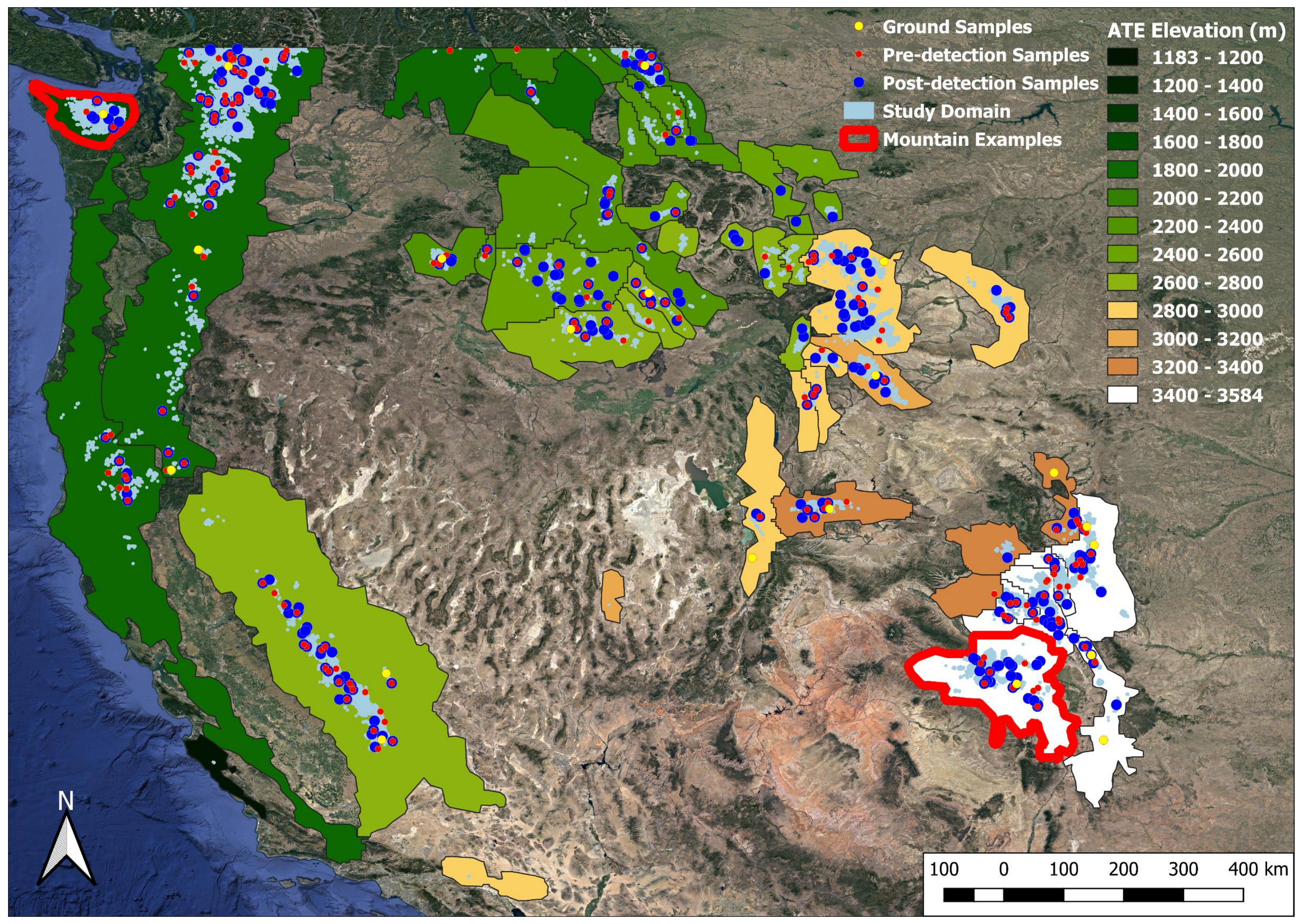


Fig. 1. ***Geographic domain*** *of this study displayed in light blue, the red dots show the locations of* ***pre-detection sampled Landsat pixels****, the blue dots indicate the locations of* ***validation Landsat pixels****, the yellow dots represent the locations of* ***selected ground sampling sites*** *from an ATE study published by Weiss et al.[11], the color of each polygon represents the* ***estimated ATE elevation*** *of each mountain range[5,6] in the western U.S., the polygons with red boundaries denote* ***two examples of mountain ranges****: the Olympic Mountains (upper-left) and the San Juan Mountains (lower-right), and the background image is from satellite imagery published by Google[3].*

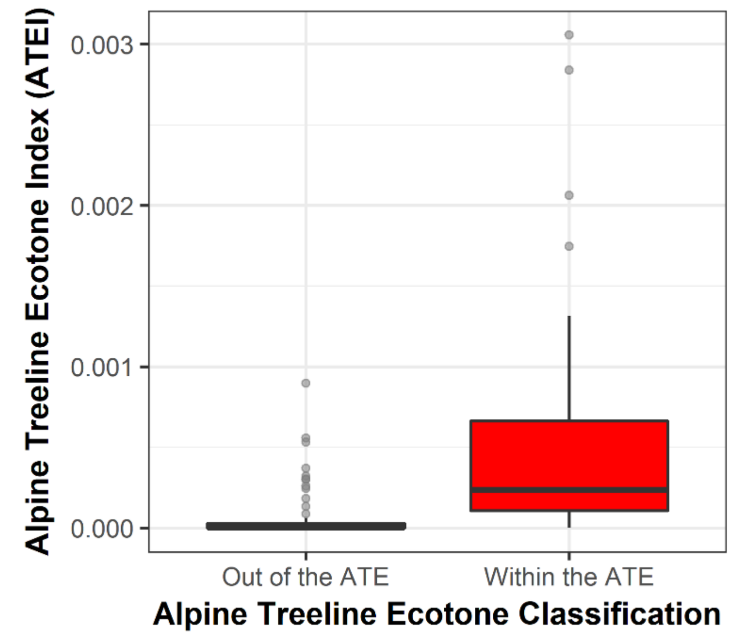


Fig. 2. *Location class and Alpine Treeline Ecotone Index (ATEI) of each validation Landsat pixel.*

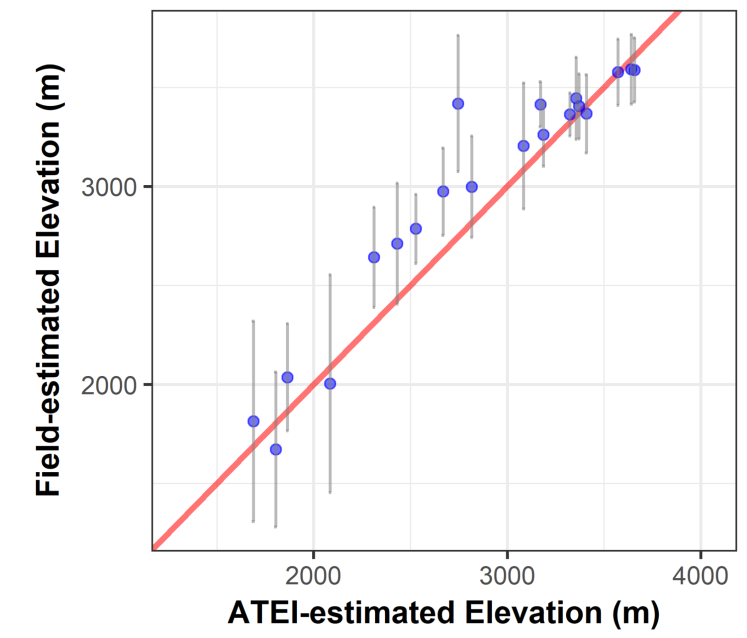
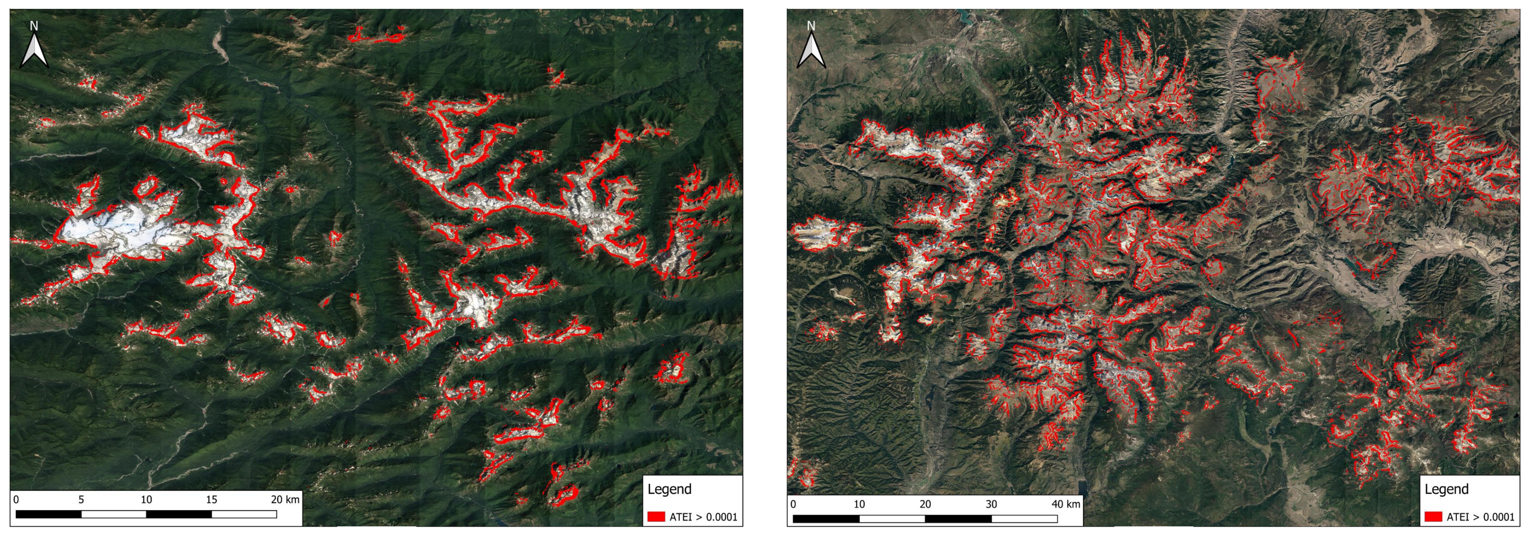


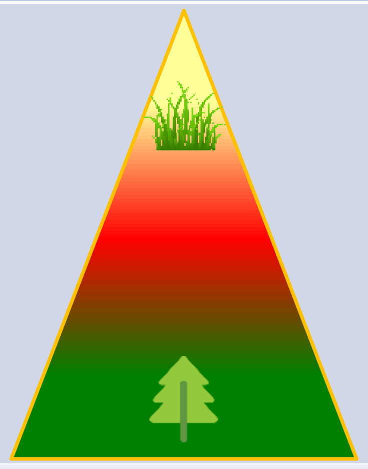
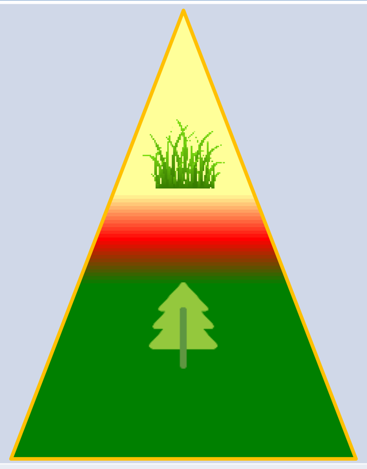
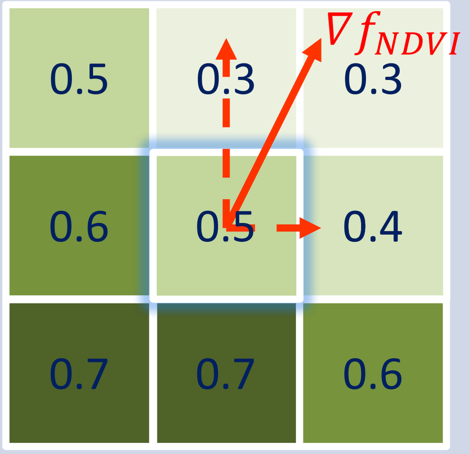
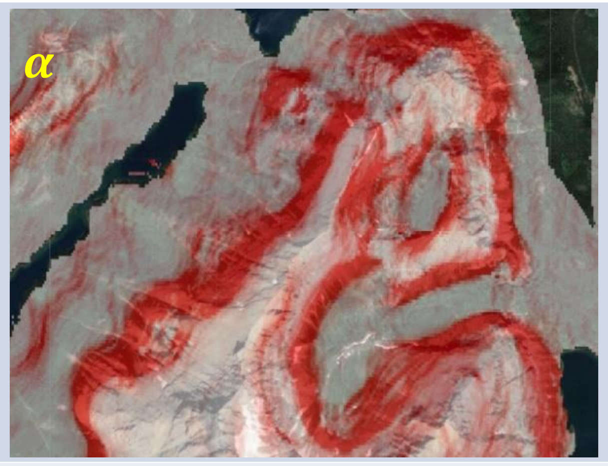
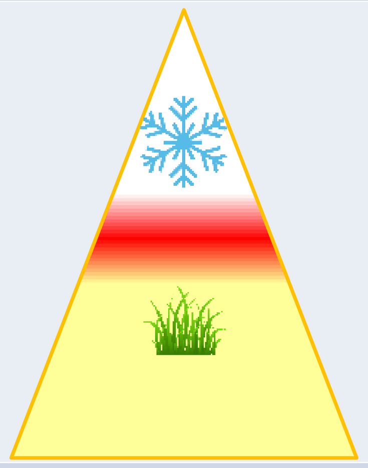
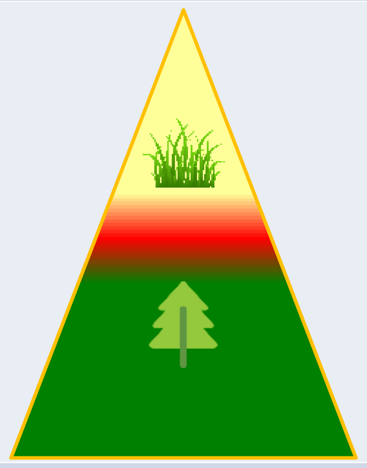
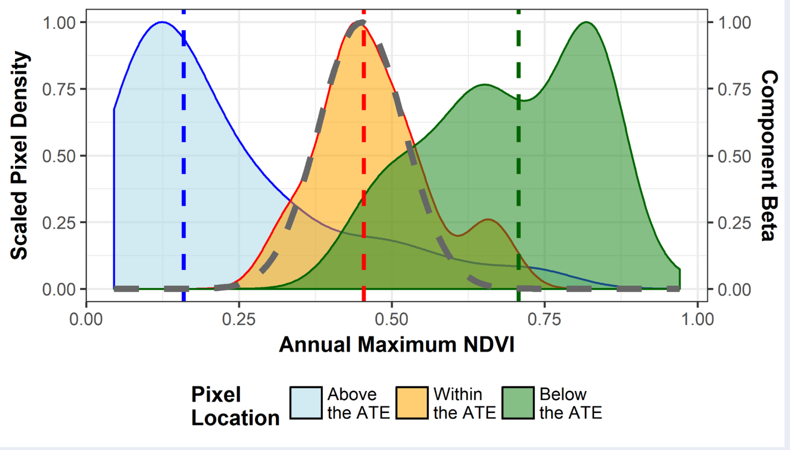
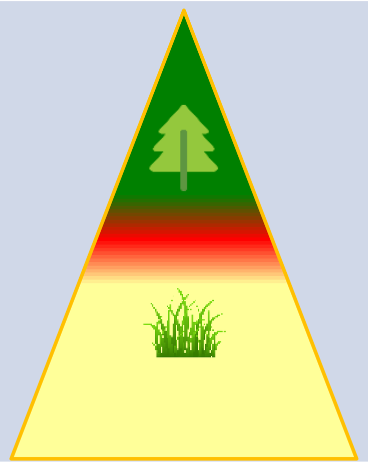
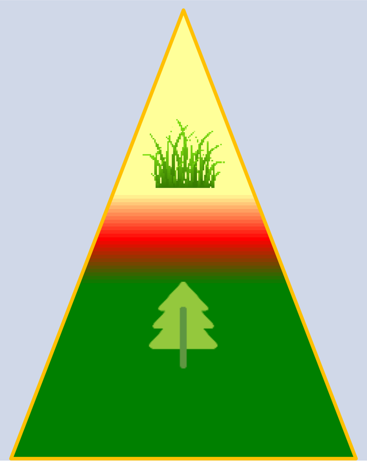
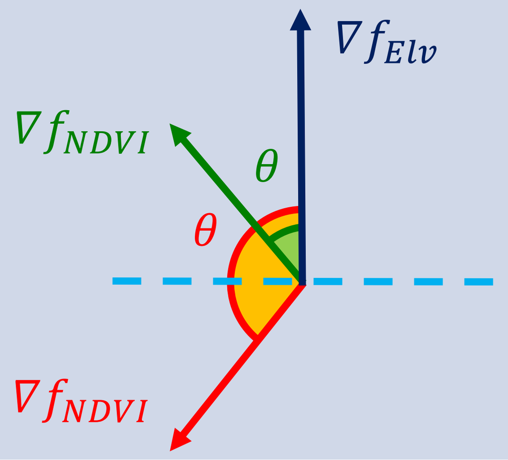
Fig. 3. *Comparison between the ATEI-estimated and the field-based[11] ATE elevations at 20 sampling sites.*



(a) (b)

Fig. 4. *Detected ATEs in two mountain-range examples (see polygons with red boundaries in Fig. 1): a) the Olympic Mountains and b) the San Juan Mountains. The two background images are both from satellite imagery published by Google[3].*

Table 1 *Index construction for the spatial detection of ATEs in the western U.S. 1)* $\boldsymbol{\alpha}$ *quantifies the magnitude of variation in vegetation relative to the direction of the elevational slope.* $\boldsymbol{\nabla f_{NDVI}}$ *denotes the image gradient of NDVI, and* $\|\nabla f_{NDVI}\|$ *is its magnitude.* $\boldsymbol{\nabla f_{Elv}}$ *represents the elevational gradient[2].* $\boldsymbol{\theta}$ *is the angle between the directions of* ∇f_{NDVI} *and* ∇f_{Elv}*. 2)* $\boldsymbol{\beta}$ *is a Gaussian function of* f_{NDVI}*, which depresses areas with very low or very high NDVI values. Its parameters are set based on the result of pre-detection sampling (a = 1, b = 0.45, and c = 0.07). 3)* $\boldsymbol{\gamma}$ *depresses areas where* ∇f_{NDVI} *and* ∇f_{Elv} *are in similar directions (θ < 90° or θ > 270°). Here, n is set to 10.*

Criterion	✗	✓	Algorithm	Component	Result
Sharp gradient in vegetation				$\alpha = \|\nabla f_{NDVI}\| \cos\theta$	
Intermediate vegetation				$\beta = ae^{-\frac{(f_{NDVI}-b)^2}{2c^2}}$	
Opposite gradient directions				$\gamma = \frac{(1-\cos\theta)^n}{2^n}$	

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Google Earth Engine RStudio QGIS

Selected References

1. DigitalGlobe, 2018. High-resolution Imagery of the Western United States from the DigitalGlobe [WWW Document]. Google Earth. URL http://www.earth.google.com (accessed 18).
2. Farr, T.G., Rosen, P.A., Caro, E., Crippen, R., Duren, R., Hensley, S., Kobrick, M., Paller, M., Rodriguez, E., Roth, L., Seal, D., Shaffer, S., Shimada, J., Umland, J., Werner, M., Oskin, M., Burbank, D., Alsdorf, D., 2007. The Shuttle Radar Topography Mission. Rev. Geophys. 45, RG2004.
3. Google Maps, 2018. Satellite Imagery from the Google Maps [WWW Document]. Google Maps. URL http://www.maps.google.com (accessed 18).
4. Karger, D.N., Conrad, O., Böhner, J., Kawohl, T., Kreft, H., Soria-Auza, R.W., Zimmermann, N.E., Linder, H.P., Kessler, M., 2017. Climatologies at high resolution for the earth's land surface areas. Sci Data 4, 170122.
5. Körner, C., Jetz, W., Paulsen, J., Payne, D., Rudmann-Maurer, K. & Spehn, E. M. A global inventory of mountains for bio-geographical applications. Alp Botany 127, 1-15 (2017).
6. Körner, C., Paulsen, J. & Spehn, E. M. A definition of mountains and their bioclimatic belts for global comparisons of biodiversity data. Alp Botany 121, 73 (2011).
7. MacDonald, G., Kremenetski, K., Beilman, D. Climate change and the northern Russian treeline zone. Philosophical Transactions of the Royal Society B: Biological Sciences, 363(1501), 2285-2299 (2008).
8. Paulsen, J., Körner, C., 2014. A climate-based model to predict potential treeline position around the globe. Alpine Botany 124, 1–12.
9. USDA Farm Service Agency, 2018. High-resolution Imagery of the Western United States from the United States Department of Agriculture Farm Service Agency [WWW Document]. Google Earth. URL http://www.earth.google.com (accessed 18).
10. USGS Earth Resources Observation & Science Center, 2018. Landsat Surface Reflectance Products of the Western United States from the United States Geological Survey Earth Resources Observation and Science Center [WWW Document]. URL (accessed 18).
11. Weiss, D.J., Malanson, G.P., Walsh, S.J., 2015. Multiscale Relationships Between Alpine Treeline Elevation and Hypothesized Environmental Controls in the Western United States. Ann. Assoc. Am. Geogr. 105, 437–453.