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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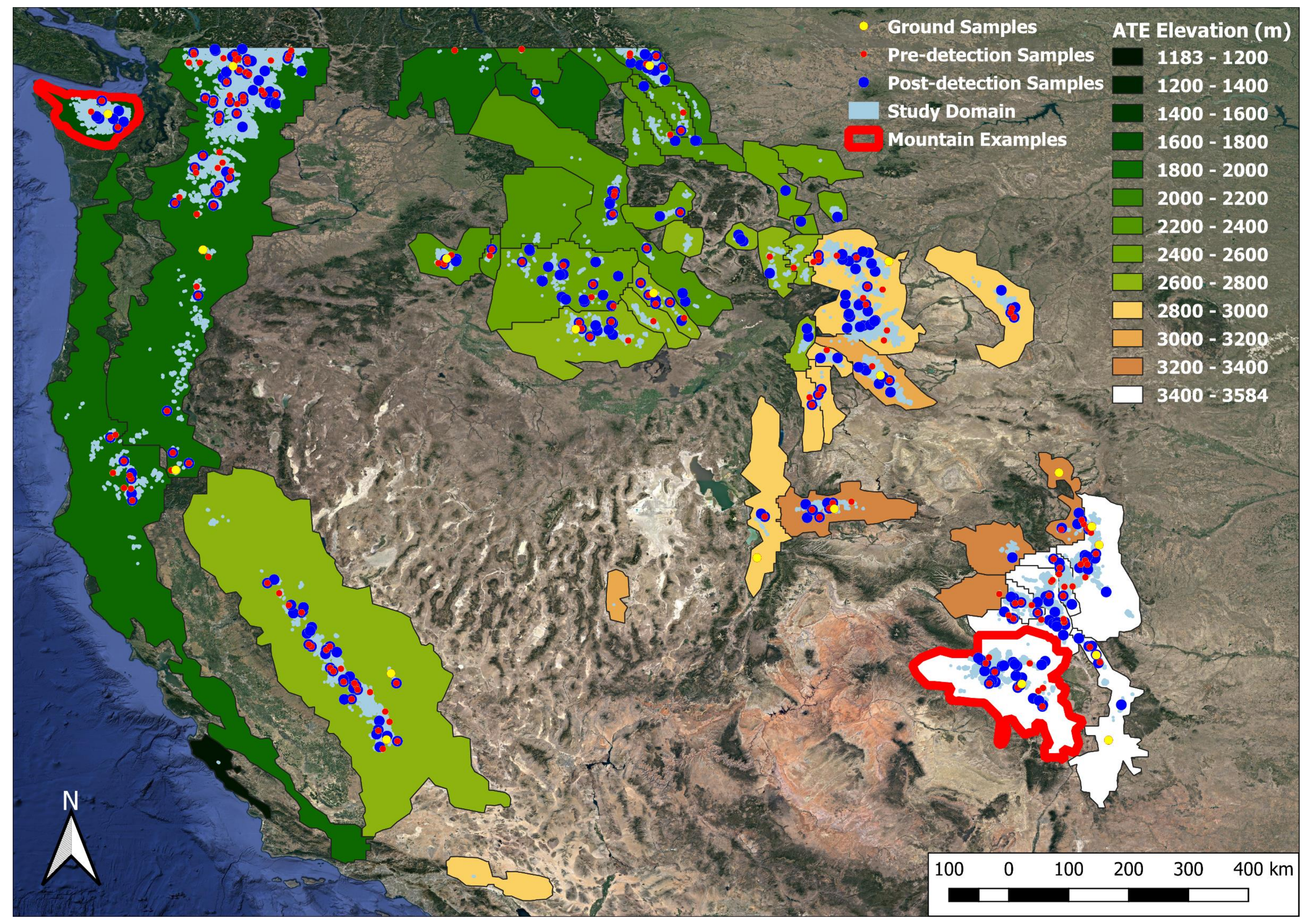


Fig. 1. ***Geographic domain*** *of this study displayed in light blue, the red dots show the locations of* ***pre-detection sampled Landsat pixels****, the blue dots indicate the locations of* ***validation Landsat pixels****, the yellow dots represent the locations of* ***selected ground sampling sites*** *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]*.*

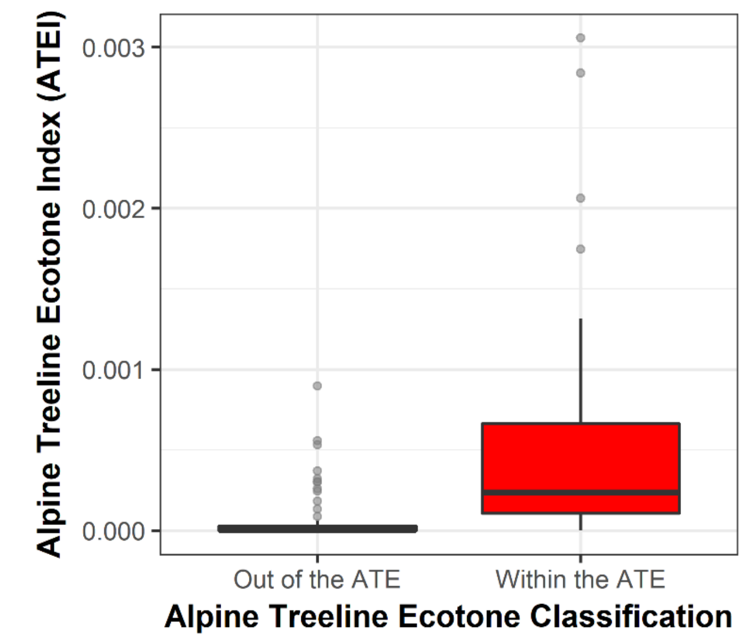


Fig. 2. *Location class and Alpine Treeline Ecotone Index (ATEI) of each validation Landsat pixel.*

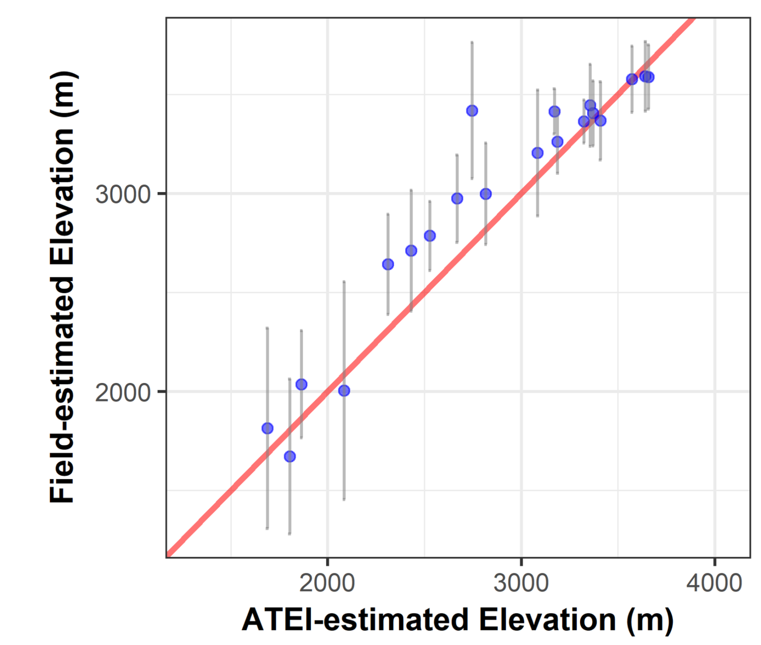


Fig. 3. *Comparison between the ATEI-estimated and the field-based*[11] *ATE elevations at 20 sampling sites.*

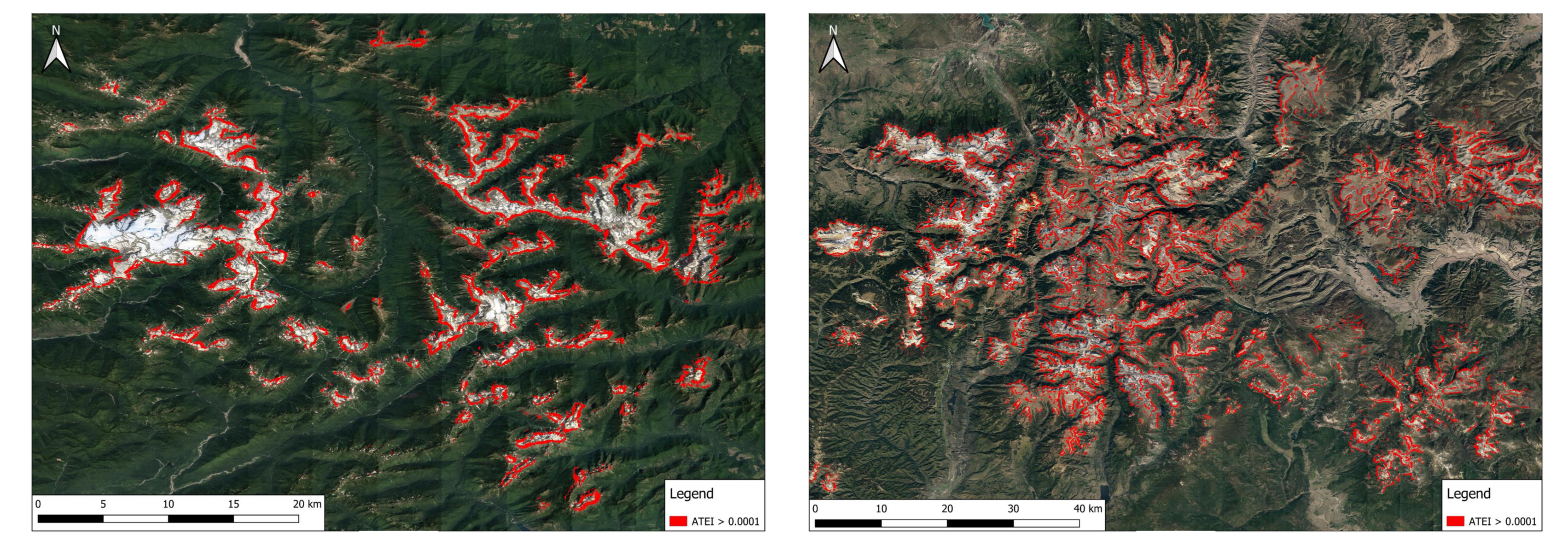
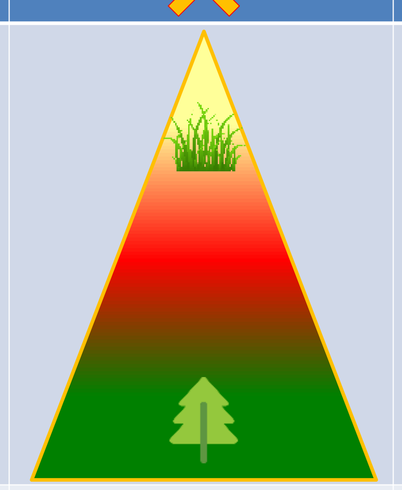
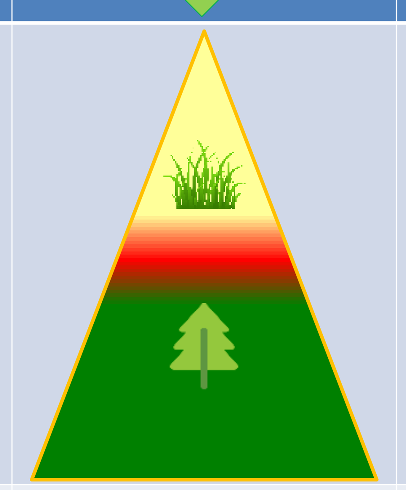
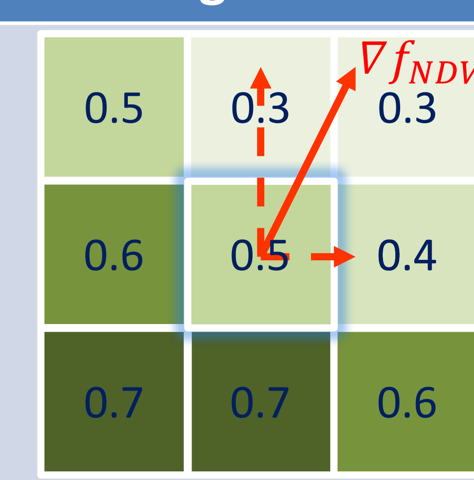
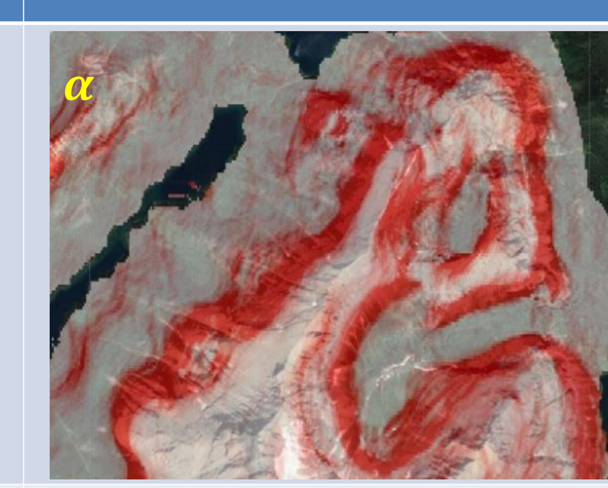
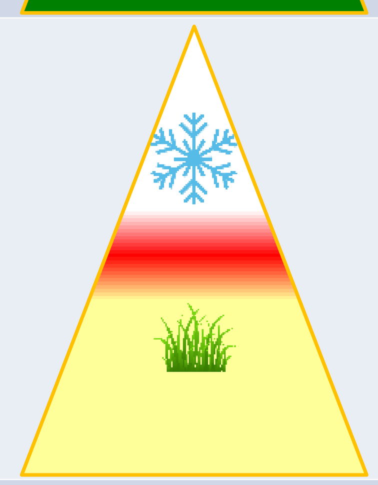
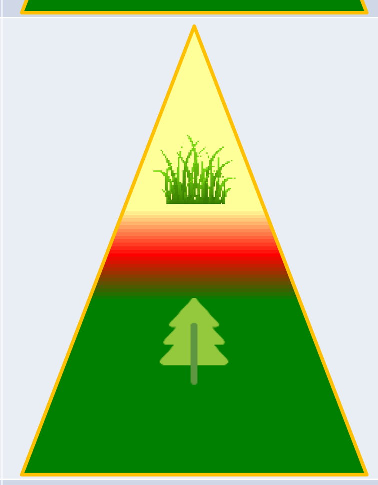
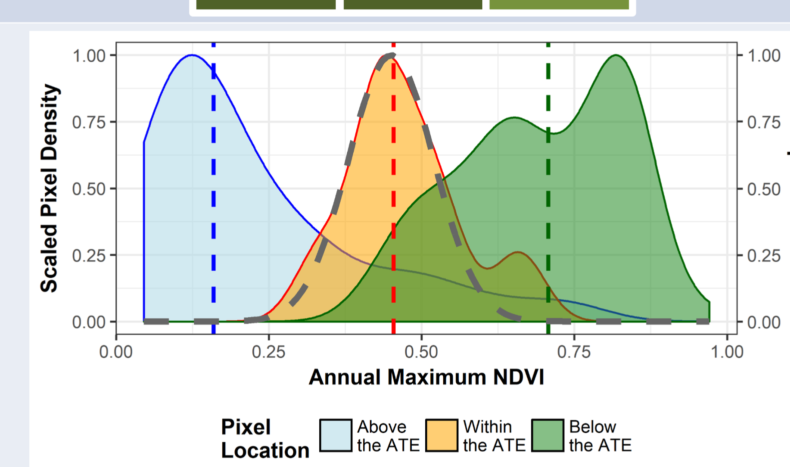
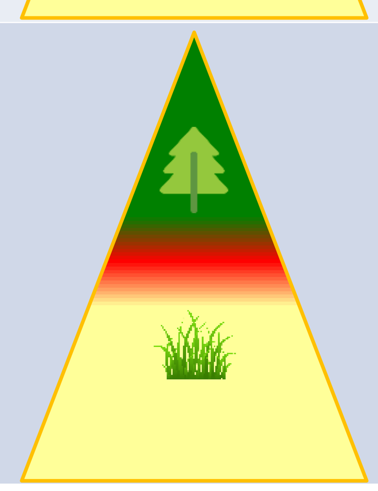
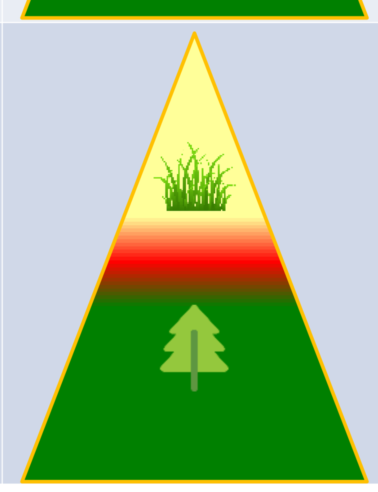
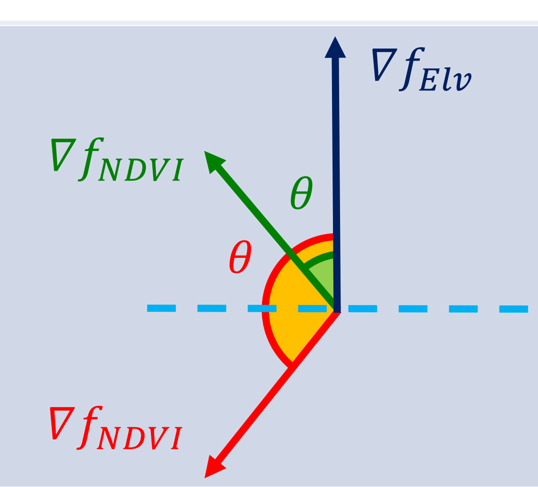
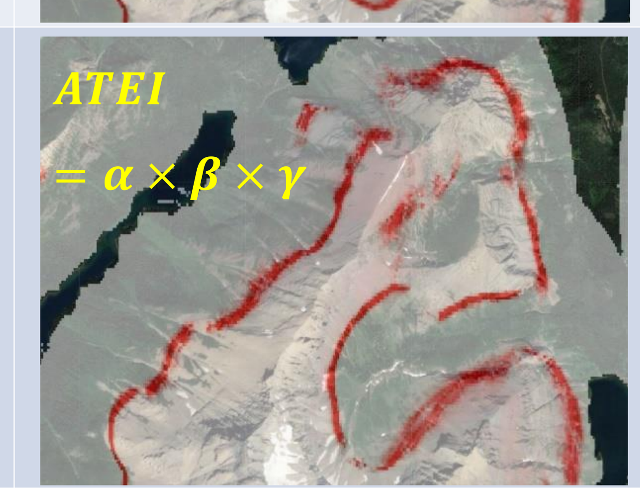


Fig. 4. *Detected ATEs in two mountain-range examples (see polygons with red boundaries in Fig. 1): a) the Olympic Mountains and b) the San Juan Mountains. The two background images are both from satellite imagery published by Google*[3]*.*

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

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