

Introduction

Land surface phenology is the temporal evolution of differential spectral reflectance in the near infrared and red wavelengths that reveals changes in the vegetated land surface (e.g., leaf out) (White et al., 2005). Seasonal changes in the Normalized Difference Vegetation Index (NDVI), a self-standardizing measure of land surface greenness, have proven useful in tracking land surface phenology and identifying areas with suspected disturbances such as storm and insect damage. In this study, we defined standard classes of annual phenological trajectories by applying an unsupervised data mining methodology to 13 years of NDVI (2000–2012). These NDVI data, retrieved from NASA's pair of Moderate Resolution Imaging Spectroradiometer (MODIS) spaceborne sensors every 8 days, covered the continental United States (CONUS) at a 250 m resolution. Next, we produced annual maps of phenological classifications (phenoclasses) that we call phenological regions or phenoregions. From these maps, we derived maps of the phenological classification mode, which provide a baseline of the expected annual phenological trajectory for every call. Areas that show significant deviations from the phenological mode are likely to be experiencing some sort of disturbance. Since our unsupervised classification scheme cannot provide a useful descriptor for individual phenoregions, we developed a method we call "label stealing" to automate the identification of phenoregions using expert-derived land cover maps. This approach reduced the map of 1000 unnamed phenoregions to maps of 235 and 197 phenoregions labeled with the best matching land cover name from 17 different land cover maps produced by various experts.

Clustering MODIS NDVI into Phenoregions

- Hoffman and Hargrove previously used k-means clustering to detect brine scars from hyperspectral data (Hoffman, 2004) and to classify phenologies from monthly climatology and 17 years of 8 km NDVI from AVHRR (White et al., 2005).
- This data mining approach requires high performance computing to analyze the entire body of the high resolution MODIS NDVI record for the CONUS.
- >87B NDVI values, consisting of \sim 146.4M cells for the CONUS at 250 m resolution with 46 maps per year for 13 years (2000–2012), analyzed using k-means clustering.
- The annual traces of NDVI for every year and map cell are combined into one 327 GB singleprecision binary data set of 46-dimensional observation vectors.
- Clustering yields 13 phenoregion maps in which each cell is classified into one of k phenoclasses that represent prototype annual NDVI traces.



Figure 1: The map of 50 phenoregions, derived from 13 years of MODIS NDVI (2000–2012), for year 2012 shown in random colors.

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·	Cluster 11	Cluster 49	Cluster 15	Cluster 48	Cluster 31	Cluster 16	Cluster 47	Cluster 20	Cluster 35	Cluster 33
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	Cluster 22	Cluster 24	Cluster 27	Cluster 4	Cluster 42	Cluster 29	Cluster 3	Cluster 38	Cluster 7	Cluster 30
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	Cluster 1	Cluster 50	Cluster 46	Cluster 9	Cluster 26	Cluster 39	Cluster 14	Cluster 12	Cluster 25	Cluster 8
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day of year

Figure 2: The corresponding 50 phenoclass trajectory prototypes sorted by area under the curve and shown in the same random colors as the phenoregion map above.







Figure 4: The mode map shows the phenoregion most frequently occupied in all 13 years. The max mode maps shows the same thing, except if there are ties, the phenoclass with the largest maximum NDVI is chosen. Principal components analysis (PCA) was used to obtain the three most dominant annual trajectories of NDVI, and these PCs were assigned to the green, blue, and red colors to produce the similarity colors map. PC1 appears to correspond to evergreen vegetation, PC2 appears to correspond to deciduous forests and crops, and PC3 appears to correspond to drought deciduous vegetation.

• Hargrove et al. (2006) developed a method for quantitatively comparing categorical maps that is 1) independent of differences in resolution, 2) independent of the number of categories in maps, and 3) independent of the directionality of comparison.

Polygon from Map 2

Polygon from

Map 2 like Map 1).

highest GOF score.





Integrating Statistical and Expert Knowledge to Develop Phenoregions for the Continental United States UCIA

[†]University of California - Irvine, [‡]Oak Ridge National Laboratory (ORNL), and *USDA Forest Service

Figure 3: Persistence of phenological classification for 50 phenoregions across all 13 years of MODIS NDVI (2000–2012). Blue regions are classified into the same phenoclass almost every year, while yellow to red regions are classified into different phenoclasses almost every year.

(a) Mode map of 50 phenoregion (random colors) Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov De

Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

(c) Principal components trajectories (similarity colors legend)



(d) Max mode map of 50 phenoregions (similarity colors map)

Mapcurves



Goodness of Fit (GOF) is a unitless measure of spatial overlap between map categories: $\sum_{\text{polygons}} \frac{C}{B+C} \times \frac{C}{A+C}$ $\mathsf{GOF} =$

GOF provides "credit" for the area of overlap, but also "debit" for the area of non-overlap.

• Mapcurves comparisons allow us to reclassify any map in terms of any other map (*i.e.*, color

• A greyscale GOF map shows the degree of correspondence between two maps based on the



(c) 50 phenoregions reclassed (d) 50 phenoregions reclassed **Figure 5:** The 50 phenoregions max mode map reclassed based on comparisons with two land cover maps.

Table 1: Two 2-way comparisons of the 50 phenoregions max mode map with two example land cover mans

Nample land	cover maps.	
Cluster	IGBP Land Cover	Olson's Global Ecoregions
1	Grasslands	cool grasses and shrubs
2	Evergreen Needleleaf Forest	cool conifer forest
3	Croplands	corn and beans cropland
4	Cropland/Natural Vegetation Mosaic	cool forest and field
5	Open Shrublands	semi desert sage
6	Grasslands	cool conifer forest
7	Grasslands	hot and mild grasses and shrubs
8	Cropland/Natural Vegetation Mosaic	cool forest and field
9	Grasslands	hot and mild grasses and shrubs
10	Open Shrublands	semi desert shrubs
11	Croplands	corn and beans cropland
12	Evergreen Needleleaf Forest	conifer forest
13	Open Shrublands	semi desert shrubs
14	Savannas	savanna (woods)
15	Grasslands	hot and mild grasses and shrubs
16	Evergreen Needleleaf Forest	cool conifer forest
17	Evergreen Needleleaf Forest	cool conifer forest
18	Evergreen Needleleaf Forest	cool conifer forest
19	Deciduous Broadleaf Forest	deciduous broadleaf forest
20	Deciduous Broadleaf Forest	deciduous broadleaf forest
21	Deciduous Broadleaf Forest	cool broadleaf forest
22	Open Shrublands	semi desert sage
23	Grasslands	cool grasses and shrubs
24	Grasslands	semi desert sage
25	Croplands	woody savanna
26	Evergreen Needleleaf Forest	conifer forest
27	Evergreen Needleleaf Forest	cool conifer forest
28	Water	inland water
29	Croplands	woody savanna
30	Grasslands	cool grasses and shrubs
31	Croplands	cool crops and towns
32	Water	inland water
33	Grasslands	cool grasses and shrubs
34	Open Shrublands	semi desert shrubs
30	Grassianos Deciduous Precedicof Forcet	not and mild grasses and shrubs
30 27	Evergroop Moodleloof Egreet	dooiduous broadloof forest
30	Evergreen Needleleal Forest	cool conifor foract
30	Grasslands	hot and mild grasses and shrubs
40	Cronlands	hroadlaaf crons
-+0 	Cropland/Natural Vegetation Mosaic	cool fields and woods
42	Cronlands	corn and beans cronland
43	Mixed Forests	cool broadleaf forest
44	Croplands	deciduous broadleaf forest
45	Cropland/Natural Vegetation Mosaic	cool forest and field
46	Cropland/Natural Vegetation Mosaic	crops. grass. shrubs
47	Evergreen Needleleaf Forest	crops, grass, shrubs
48	Croplands	corn and beans cropland
49	Deciduous Broadleaf Forest	cool broadleaf forest
50	Grasslands	cool grasses and shrubs
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 The consistency between the two sets of labels from expert maps suggests that this approach provides an automated method for adding expert supervision to our unsupervised classification scheme.

following 17 maps were used for "label stealing."

Foley Land Cover
 DeFries UMd Vegetation Foley Land Cover Fedorova, Volkova, and Varlyg GAP National Land Cover Holdridge Life Zones Küchler Types BATS Land Cover IGBP Land Cover Olson Global Ecoregions Seasonal Land Cover Regions Seasonal Land Cover Leemans-Holdridge Life Zones Matthews Vegetation Types Mator Land Resource Areas National Land Cover Database Wilson, Henderson, & Sellers I Landfire Vegetation Types

no descriptive labels like **Eastern Deciduous Forest Biome**.

- human-created descriptive labels to assign to phenoregions.
- We employ the Mapcurves GOF to select the best ecoregion labels from ecoregionalizations drawn by human experts.
- the label with the highest GOF score for every phenoregion polygon.

Forrest M. Hoffman^{†‡}, Jitendra Kumar[‡], and William W. Hargrove*

• A wide variety of expert-derived land cover class maps are available. The



Label Stealing

Clustering is an unsupervised classification technique, so phenoregions have

• Label stealing allows us to perform automated "supervision" to "steal" the best

• We consider an entire library of ecoregion and land cover maps, and choose

 (a) 1000 phenoregions max under, (mode with largest area under the curve, random colors) (b) 1000 phenoregions reclassed into 235 land cover types (random colors) (c) Goodness of Fit (GOF) map for 1000 phenoregions reclassed into 235 land cover types (millarity colors) Figure 6: The 1000 phenoregions max under map was compared with all 4 seynert-derived maps using the Mapcurves method. The result was a list of 23 land cover types (millarity colors) Figure 6: The 1000 phenoregions max under map was compared with all 4 seynert-derived maps using the Mapcurves method. The result was a list of 23 land cover types (millarity colors) Figure 6: The 1000 phenoregions max under map was compared with all 4 of the 17 maps, yielding a reclassified may of these 235 named regions. Table 2: Abridged list of 235 expert-derived labels corresponding to the 100 phenoregions. Catland Cover Label Acadam Low-Elevation Spruce-Fit-Hardwood Forest Appine meadows & barren Appine meadows & barren Buestem Hils, MLRA 76 California Central Valley and Southern Coastal Grasstand California Central Valley Mad Cole Savanna California Central Valley Mad Cole Savanna California Steppe California Steppe California Steppe California Steppe California Steppe Marting Contral Valley Mad Cole Savanna California Steppe Californi		
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Table 3: Scoring the experts. This table lists the 14 of 17 expert-derived lan	Cat Land Cover Label 1 Acadian Low-Elevation Spruce-Fir-Hardwood 2 Agriculture-Pasture and Hay 3 Alpine meadows & barren 4 Barren 5 Barren or Sparsely Vegetated 6 Bluestem/Grama 7 Bluestem/Grama 7 Bluestem/Grama 7 Bluestem/Grama 7 Bluestem Hills, MLRA 76 8 Boreal 10 Boreal 10 Boreal moist forest 11 Broadleaf Deciduous Forest 12 Brown Glaciated Plain, MLRA 52 13 California Central Valley and Southern Coas 14 California Central Valley Mixed Oak Savanna 15 California central Valley Mixed Oak Savanna 15 California steppe 222 Warm temperate moist forest 223 Warm Temperate Moist Forest 224 [water] 225 Water 226 Western Great Plains Mesquite Woodland and 227 Western Great Plains Sho	Land Cover Map d Forest landfire vegetation type landfire vegetation type landcover.slcr landcover.slcr landcover.usgs ktlamb mIra foleylandcover fvvcode holdridgezonesnormal landcover.usgs tal Grassland GAP 240m laea a GAP 240m laea ktlamb

Мар	Cats	WCats	WClusts	%Area
10. Seasonal Land Cover Regions	194	43	160	19.45
9. Olson Global Ecoregions	49	12	96	12.36
 Fedorova, Volkova, and Varlyguin World Vegetation Cover 	31	4	93	10.69
17. Landfire Vegetation Types	443	27	85	9.09
6. Küchler Types	117	34	81	7.87
14. Major Land Resource Areas	197	42	107	7.18
12. Leemans-Holdridge Life Zones	26	8	54	5.27
11. USGS Land Cover	24	7	21	4.85
4. GAP National Land Cover	578	19	124	4.48
5. Holdridge Life Zones	25	9	38	4.15
2. Foley Land Cover	14	7	48	3.86
15. National Land Cover Database 2006	16	8	47	3.24
13. Matthews Vegetation Types	19	5	18	2.49
16. Wilson, Henderson, & Sellers Primary Vegetation Types	23	2	9	1.46
7. BATS Land Cover	17	4	10	1.23
8. IGBP Land Cover	16	3	4	0.80
1. DeFries UMd Vegetation	12	2	5	0.25
TOTAL		235	1000	100%



• We judiciously merged categories through a manual process, reducing the 235 labels down to 197 labels.



 Table 4: Abridged list of 197 expert-derived labels corresponding to 1000 phe noregions after judicious manual merging.

# (Cat Land Cover Label	Land Cover Map	% Area
1 ·	176 Subboreal	fvvcode	5.28%
2	179 Subtropical	fvvcode	4.25%
3	73 Evergreen Coniferous Forest	landcover.usgs	3.87%
4	67 Open Shrubland	foleylandcover	3.74%
5	35 corn and beans cropland	landcover.oge	3.48%
6	29 cool conifer forest	landcover.oge	2.93%
7	32 Cool temperate moist forest	holdridgezonesnormal	2.55%
8	64 Desert Shrubland/Grassland (Creosote, Saltbush, Mesquite, Sand Sage)	landcover.slcr	2.27%
9	55 Deciduous Forest (Oak, Hickory, Sweet Gum, Southern Pines) with Cropland and Pasture	landcover.slcr	2.25%
10	28 cool broadleaf forest	landcover.oge	2.23%
11	66 Sparsely Vegetated Desert Shrublands	landcover.slcr	2.14%
12 ⁻	188 Warm temperate moist forest	holdridgezonesnormal	2.06%
13 ⁻	180 Subtropical moist forest	holdridgezonesnormal	2.05%
14 ⁻	160 semi desert sage	landcover.oge	1.87%
•	· · · · · · · · · · · · · · · · · · ·	• •	• •
187 ⁻	120 Northern hardwoods/Spruce	ktlamb	0.01%
188 ⁻	102 Laurentian-Acadian Alkaline Conifer-Hardwood Swamp	landfire vegetation type	0.01%
189	51 NASS-Vineyard	landfire vegetation type	0.01%
190	2 Alpine meadows & barren	ktlamb	0.01%
191 ⁻	143 Pseudotsuga menziesii Forest Alliance	landfire vegetation type	0.01%
192 ⁻	134 Olympic and Cascade Mountains, MLRA 3	mlra	0.01%
193	79 Evergreen Needleleaf Forest (Lodgepole Pine and Douglas Fir)	landcover.slcr	0.01%
194 ⁻	125 North Pacific Maritime Mesic Subalpine Parkland	GAP 240m laea	0.00%
195	80 Evergreen Needleleaf Forest (Lodgepole Pine, Englemann Spruce, Ponderosa Pine)	landcover.slcr	0.00%
196 ⁻	157 Saltbrush/Greasewood	ktlamb	0.00%

Conclusions

- The Mapcurves approach can be successfully applied to steal ecoregion, land cover, or vegetation type labels for unsupervised classifications.
- We can envision a wide variety of uses for this label stealing procedure, includ-
- Automated attribution of disturbance agents through comparison of a U.S. Forest Service ForWarn system disturbance map with Aerial Detection Survey (ADS) sketchmaps, wildfire perimeters, tornado track maps, and fuel treatment maps through time.
- Determination of the most important driving variable for phenoregions maps through comparison with separate maps of slope, aspect, solar input, elevation, soil types, etc.
- -Automated recognition of species composition of forest vegetation through comparison of a phenoregions map with individual tree species range maps.

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