# Temporal signatures and harmonic analysis of natural and anthropogenic disturbances of forested landscapes: a case study in the Yellowstone region

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*Abstract*-**Diversity patterns observed for a given landscape are dependent on the spatial and temporal scales of the investigation. In this research the temporal response was investigated within the undisturbed mature forests of the Yellowstone region, the 1988 fire burns and the harvested forest tracks in Targhee National Forest. The satellite data set employed for this analysis was the 1989 to 2001 weekly NOAA AVHRR NDVI composite. Harmonic analysis was used to express the cyclical NDVI curve as a sum of a series of cosine waves and an additive term. Two research questions were addressed: 1) Can interannual and seasonal patterns for the various disturbed and undisturbed forested landscapes be discerned? 2) How do the interannual and seasonal patterns vary for undisturbed, naturally disburdened and human impacted forest landscapes? The changes in amplitude, phase and variance for the most explanatory harmonic term were compared between the two disturbance types and the undisturbed forests. The findings show that interannual and seasonal patterns differ with disturbance type and both differ from undisturbed forests. Mature forests are the most difficult to predict for interannual and seasonal patterns, predictability is easiest for young, post disturbance areas. Finally, the results show that natural forests are temporally diverse.**

## I. INTRODUCTION

The spatial and temporal composition and structure of a landscape is an important biodiversity feature to monitor because changes to the landscape can impact the basic environments necessary for functioning at all levels of biodiversity. Field data and other data sources are often implemented in biodiversity monitoring schemes to study the landscape processes and patterns over time [1]. Such monitoring protocols lead to the application and development of change detection methodologies. These methodologies require data that have a large spatial extent, a temporal component and are effortlessly integrated with other spatial analysis technologies, such as Geographic Information Systems (GIS).

Satellite remote sensing has long held promise as a powerful method of detecting forest changes and mapping landscape structure over vast, often multi-jurisdictional forest areas. By analyzing information from Landsat Thematic Mapper (TM) and NOAA Advanced Very High Resolution Radiometer (AVHRR), the spectral response or Normalized Difference Vegetation Index (NDVI) of these sensors can be related accurately to changes in physiology and cover at a range of small to large mapping scales. These data have been available continuously for almost 20 years; many areas have earlier satellite image archives stretching back to the 1970s. When considering spatially-explicit changes to landscapes—caused by natural and human disturbances—over this time period, digital, synoptic, and repeatable satellite remotely-sensed data are emerging as the observational media of choice that forest managers must possess and use wisely. Change detection methods are beginning to emerge as an imperative tool to forest mangers and biodiversity monitoring programs. A number of approaches for change detection using remotely sensed multitemporal data sets are described in the literature [2]. Other methods have been developed for multitemporal change detection focusing on the spatial patterns of the managed landscape and the temporal changes captured by these spatial patterns [3]. Such methods apply landscape metrics to quantify the spatial changes occurring in a landscape and relate these to disturbance types such as fire, insect damage or forest harvesting. However, these methods are best applied to multitemporal data, and are not implemental to monitoring landscape change with hypertemporal time-series data, such as bi-weekly or weekly NDVI composites of AVHRR imagery. Thus, the temporal patterns of disturbed landscapes cannot be effectively quantified or monitored with these tools. Harmonic analysis, also known as Fourier analysis, can be used to express the cyclical NDVI curve as a sum of a series of cosine waves (defined by a phase and amplitude value) and an additive term. Such approach can be used to analyze sets of successive regular multidate samples of satellite remotely sensed imagery. The application of this method to time-series AVHRR NDVI data in the characterization for natural and agricultural land use/land cover was demonstrated by Reference [4]. The interannual changes in natural and manmade vegetation have also been investigated using the time-series analysis of AVHRR



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NDVI data [5]. This research has shown that harmonic analysis is effective in detecting periodic patterns in time series of satellite imagery for quantifying changes in periodic seasonal NDVI over time. Such periodic patterns can have significant relationships with the biodiversity of the forested landscape. Biodiversity exist within the context of the landscape, the spatial and temporal background supporting various activities and interactions within and among ecological complexes. Furthermore, wildlife or species diversity may be directly related to the diversity of a landscape [6]. Thus, if a landscape is to be managed effectively, a monitoring strategy needs to quantify the temporal diversity of a landscape. Such diversity can be monitored on seasonal and interannual scales, and can vary with the succession gradient of the forest. As of the time of this project no known work of seasonal and interannual time-series patterns has been related to forest biodiversity.

*Objectives*

The main goal of this research was to demonstrate the merit of harmonic analysis methods in application to landscape change in forested ecosystems. Specifically, the diversity in temporal patterns for different forest disturbance types were addressed through two research objectives:

1) Can interannual and seasonal patterns for the various disturbed and undisturbed forested landscapes be discerned?
2) How do the interannual and seasonal patterns vary for undisturbed, naturally disburdened and human impacted forest landscapes?

## II. METHODOLOGY

*Study Area*

The study area lies in the central northwestern United States approximately within 46°N 112°W to 42°N 108°W, and spans the states of Idaho and Wyoming (Figure 1). The location was chosen because it features multi-jurisdictional forest areas consisting of the Targhee National Forest (TNF) and Yellowstone National Park (YNP). Different forest management strategies and disturbance scenarios prevail in the adjacent lodgepole pine (*Pinus contorta*) forests. For example, the Targhee National Forest has undergone extensive harvesting activities, but forests have been allowed to reach maturity within the Yellowstone National Park boundary. The date of the 1988 fires in Yellowstone National Park can also be matched with a 1988 harvesting date of a lodgepole pine stand in the Targhee National Forest, assuring that the manmade and naturally disturbed areas are recovering commencing with the same date. The region landscape varies, from mountainous to plateaus. Climate in the region ranges from cold and moist in the mountainous areas to temperate and semiarid in the plains areas. Annual temperature extremes range from less than -20°C during the winter to greater than 30°C degrees during the summer.

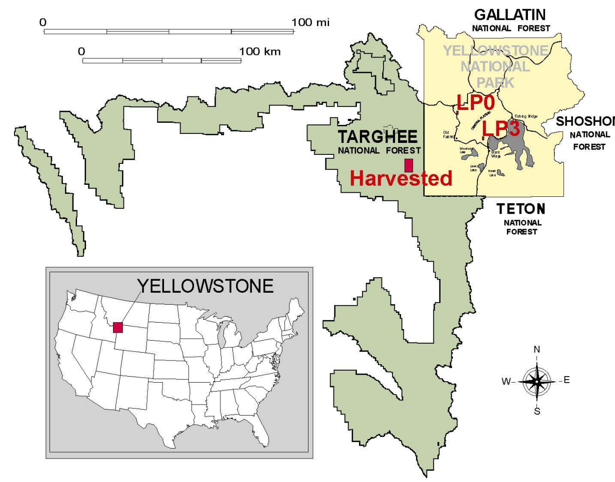


Figure 1. Study area, Yellowstone National Park is shown in yellow, Targhee National Forest is shown in green, sampled field and GIS data sites are shown in red.

The study area has been divided into three major vegetation zones [7]; the lodgepole pine zone, lies between 2100 m and 2600 m elevation with precipitation range of 500-900 mm annually. The Reference [7] cover type classification for Yellowstone uses a letter code to designate the species (LP = lodgepole pine) and a numerical code (0, 1, 2, 3) to indicate the relative stage of development of the forest stand. This study focused on two development stages or age classes of the coniferous forest. Forest defined as LP0 are at the initial post fire regeneration stage. The NDVI values for this type of a stand are low but can be a poor indicator of biomass if cover is poor [8], [9], because other vegetation as well as snags and deadfall can play a large role in the reflectance characteristics of this type of a stand. The LP3 stands are approximately 250 to 350 years old and are comprised mostly of subalpine fir (*Abies lasiocarpa*) and Engelmann spruce (*Picea engelmanni*). The vertical structure in these types of stands is very complex, the NDVI values are usually high but can be influenced by shadows [8], [9].

*Data*

Two satellite remotely sensed imagery types were applied in this research. First the higher 30 m per pixel resolution, 1988 Landsat TM and 2001 Landsat ETM scenes, spanning the study area, were used to select areas representative of: forest burned in 1988 (LP0), mature forest (LP3) and forest harvested in 1988 (har). Field data, consisting of 50 field sites, from a previous research in the same study area [10] were used to identify and validate the LP0 and LP3, also seen in Figure 1. A harvesting history GIS coverage, provided by the Targhee National Forest, was used to determine a location of a 1988 harvest block, shown in Figure 1. The sites selected were restricted to areas of low topographic variability. For comparative purposes a forested area of intermediate age with a very even canopy and little understory (LP0), and an agricultural region (agr) were also identified. The second data set employed was the,



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1 km per pixel resolution, NOAA-AVHRR NDVI weekly composites, obtained from U.S. Geological Survey EROS Data Center in Sioux Falls, South Dakota. Additional image processing and interpolation of missing data were preformed at the Kansas Applied Remote Sensing (KARS) Program, in Lawrence, Kansas. The weekly composites consist of the maximum NDVI value within each weekly period and the previous weekly periods for each pixel. The vegetation index data are rescaled by EROS during pre processing from a range of –1 trough 1, to 0 trough 200. Values less than 100 typically represented non-vegetated Earth surfaces. From 1989 trough 2001 the AVHRR sensor data has been obtained from three different satellites: NOAA-11 up till the end of year 1994, NOAA-14 till the end of year 2000, and NOAA-16 in the present. Sensor drift can be associated and observed in the data collected as an old sensor is phased out and a new sensor is phased in [11]. No know correction is available, or has been preformed on the AVHRR weekly NDVI data. AVHRR weekly NDVI composite data set consists of 52 periods per year and spas 13 years from 1989 to 2001, equaling 676 bands of data. Same regions were identified in the AVHRR imagery and preliminary NDVI comparisons, were made between the two data sets. Data were extracted from the areas of interest, for actual and harmonic data in ERDAS Imagine using the 'pixel to ASCII' function. Data were analyzed and graphed using desktop statistical and graphing software packages.

*Harmonic Analysis of Interannual Trends*

Using the harmonic analysis discussed by Jakubauskas el al. 2001, the AVHRR weekly NDVI data set, consisting of 52 periods, was analyzed to determine interannual trends, in the three areas of interest (LP0, LP3 and har). Fourier Machine software (Jakubauskas et al. 2000) was applied for this purpose. Thirteen harmonics were produced to determine the interannual variability of the thirteen-year data set, thus, the 13$^{th}$ harmonic conforms to the interannual NDVI variability. Graphs of the harmonic terms, term composites and comparisons to original AVHRR weekly NDVI data were produced in a desktop statistical/graphing software package.

*Harmonic Analysis of Seasonal Trends*

The AVIRIS weekly NDVI data set was subdivided into 13 yearly images consisting of 52 periods each. Fourier Machine was utilized on each of the individual year AVHRR weekly NDVI data composites to produce 7 harmonics explaining the seasonal variability of the NDVI for the three areas of interest. The number of harmonics was reduced because in such as short temporal period a fewer harmonics were required to explain the variability in the NDVI. This type of yearly analysis also helped in reducing the effect of sensor drift and the results of that effect on NDVI data and subsequently the harmonics obtained from the data. Statistical analysis was undertaken to determine the RMSE for the sum of the harmonics and the actual AVHRR NDVI, for the seasonal and interannual harmonic analysis.

## III. RESULTS AND DISCUSSION

Natural and manmade landscapes as well as undisturbed mature forests in the study area exhibit characteristic values both in the Landsat ETM NDVI imagery and the AVHRR weekly NDVI imagery, as shown in Figure 2. There is a strong linear relationship of $R^2$ 0.72 between the two NDVI data sources. As the forest age cohort increases so do the NDVI values for both of the data sets. The AVHRR weekly NDVI for the forest burned in 1988 (LP0) was ~143, compared to the LP1 value of ~162 and the mature forest (LP3) value of ~168. These increases in NDVI can be attributed to the accumulation of green biomass as the forest matures, increasing the absorption of the red wavelength band by chlorophyll for photosynthesis and increasing the scattering in the near-infrared as the structural component of the forest increases with age. Very high NDVI values are observed for the forest harvested in 1988. In the thirteen years of growth back it is apparent that a very high volume of biomass has accumulated in this stand to reflect such a high response in NDVI. Although the fire regenerating areas were disturbed at the same time, the accumulation of biomass in this naturally regenerating area is much lower. These results suggest that the harvested forest is regenerating faster post the man made disturbance, then the naturally regenerating post fire forest, mainly due to intensive re-seedling attempts.

By visually interpreting the AVHRR weekly NDVI patterns we infer that the NDVI peak for the forest

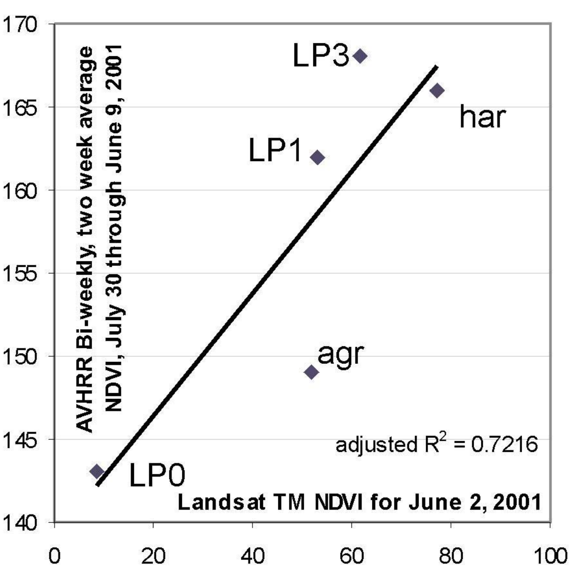


Figure 2. June 2, 2001 Landsat ETM based mean NDVI values and mean AVHRR NDVI weekly composite values for the week of June 2, 2001 for five areas of interest.

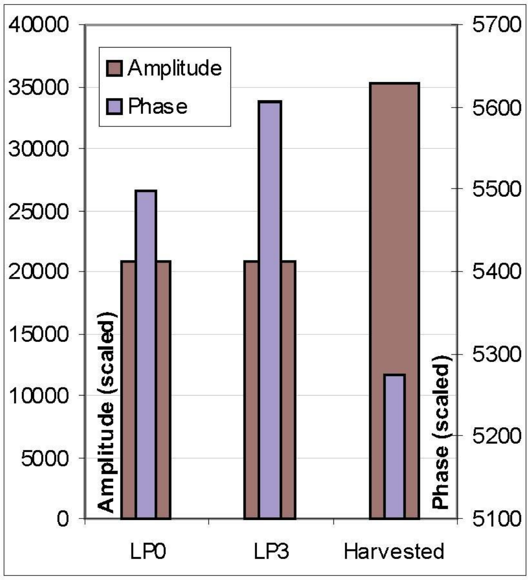


Figure 3. Interannual trends in phase and amplitude for the three areas of interest.

harvested in 1988 occurs earlier in the year as well as it is much greater then the naturally regenerating forest (LP1) or the mature forest (LP3). This supports the one time period results observed in Figure 2. The curves show that the NDVI values for the harvested block dramatically drop during the winter months, as compared to the mature forest. The LP1 site experiences a similar, but not as drastic drop in the winter NDVI values.

*Interannual Trends*

The thirteen-year harmonic analysis determined that the 13$^{th}$ harmonic explains most of the variability in the AVHRR weekly NDVI values, the lesser harmonics contribute minute explanation. However, when individual areas of interest are compared it can be observed that only 92.4% of the variance is explained by the 13$^{th}$ harmonic for the mature forest (LP3), as compared to 97.1% for the LP1 burn area and 98.4% for the harvested forests. These results suggest that the more complex mature forests are not as easily modeled by the harmonic analysis compared to the younger regenerating forests, similarly work has shown that Landsat TM NDVI values for mature forests are more variable [12].

The 13$^{th}$ harmonic is the most dominant harmonic, but once more the lesser harmonics in the mature forest still show some contribution. It can be observed that it is in the harvested forest that only the 13$^{th}$ harmonic representing the annual variably of the forest. The results suggest that man disturbed and managed forests are simpler and more static over time in their temporal dynamics and a harmonic curve can conform to these well.

Observations show that the harvested forest NDVI curves are much taller and steeper then the mature and the burned forest sites, similar to observations in Figure 2. This is also reflected in the amplitude and in the phase values of these three locations Figure 3. The lower phase of the harvested landscapes indicated an earlier green-up at this site, the greater amplitude indicated that the green-up is also stronger. The green-up at the two natural forested landscapes is of the same amplitude or strength, but it occurs later in the year in the mature forests. The natural regenerating forests and the mature forests also show greater variability in the AVHRR weekly NDVI curve for all 13 years as opposed to less variable harvested forest site. The high, steep NDVI peaks expressed in the NDVI predicted and raw curve for the harvested forest landscape can be attributed to quickly growing vegetation more suitable for tree planting, similar to agricultural crops shown in the bottom graph. Thus, cultivated landscapes are more similar to one another then to natural landscapes.

*Seasonal Trends*

The individual harmonic analysis for the 13 years showed that for each year the 1$^{st}$ harmonic was responsible for explaining most of the AVHRR weekly NDVI variability. On average over 96.5% of the variability was explained with this harmonic for all years and all sites of interest. The RMSE between the sum of four harmonics and the actual AVHRR weekly NDVI is shown as a red line between the points. The results of this analysis further support the interannual analysis results, specifically, the RMSE errors for the two natural forests are much greater then the RMSE errors for the harvested forest. Thus, even the seasonal patterns are more predictable for a man- managed forest then for a natural undisturbed or regenerating forest. More importantly, the seasonal trends for the three sites of interest are revealed through a yearly analysis. The harvested forest shows a unimodal predicted green-up curve, which fits tightly to the actual AVHRR weekly NDVI. However, both the burned forest and the mature forests show a green-up curve that is more bi-modal in shape, hinting at the complexity of the photosynthetic activity in these forests. It can be deduced from the interpretation of such curves that the natural young and mature forests show a more complex patterns of green up then the harvested and replanted forest. This is likely due to the replanting of a uniform species in the harvested forest that responds similarly to climatic variables controlling the photosynthetic cycle capture by the green-up curve. The more complex natural patterns experience a bi-modal green-up pattern as different species compete through the season for light availability. Thus, we can deduce that the natural forest are more temporally diverse then the harvested and replanted forest.

The three different areas of interest in the study area exhibited characteristic additive terms, amplitude and phase components for each year of the AVHRR weekly NDVI harmonic analysis. Trend lines were added to the graphs. Because the analysis was performed individually for each year, the trends should not be associated with the sensor drift experienced by the three NOAA satellites spanning the time of this research. The highest phase and amplitude



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values occurred in mature forest where there is the greatest amount of photosynthetic activity, due to higher green biomass, as compared to regenerating forest. The phase of the first harmonic for the mature forest drops over time, but opposite occurs in the regenerating forests, where the phase increases over time. This suggests that as forest mature the onset of green-up begins earlier and earlier in the year as gaps open up in the canopy and photosynthetic activity is undertaken by the newly exposed and establishing plants. In a regenerating forest the onset of green-up occurs later and later in the year as competition drives the canopy to closure and the early season species are out-competed by the upper canopies. These trends could be capturing a directionally temporal forested landscape change.

In the seasonal analysis of the RMSE of the sum of all 7 harmonicas and the AVHRR weekly NDVI for the 13 years and the three areas of interest is shown in the RMSE errors are highest for the mature forest, thus, the seasonal patterns of a mature forest were more difficult to predict or model then seasonal patterns of the two younger forests.

## IV. CONCLUSIONS

The harmonic analysis of the time-series data provided a replicable method of quantifying and monitoring the temporal diversity of various forested landscapes. The method showed that the natural forests are more temporally diverse then the harvested and replanted forest, this is evident in the interannual and seasonal temporal trends. A directional change in the forested landscape might be possible with the harmonica methodology and should be investigates with more sample sites representing various succession stages of the forest.

## ACKNOWLEGMENTS

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## REFERENCES

[1] Gardne, R.H., O'Neill, R.V., and Turner, M. G. (2001). Landscape Ecology in Theory and Practice: Pattern and Process. Springer Verlag, Los Angeles. 401 p.

[2] Lunetta, R.S. and C. D. Elvidge. (2000). Remote Sensing Change Detection: Environmental Monitoring Methods and Applications. Taylor & Francis, New York 318 p.

[3] Franklin, S.E., E.E. Dickson, D.M. Farr, M.J. Hansen and L.M. Moskal. 2000. Quantification of landscape structure using maps developed by satellite remote sensing. Forestry Chronicle. 76(6): 877-886.

[4] Jakubauskas, M.E., Peterson, D.L., Kastens, J., and Legates, D.R. 2002. Time-series remote sensing of landscape-vegetation interactions in the Southern Great Plains. Photogrammetric Engineering and Remote Sensing, 68 (10):1021-1030.

[5] Jakubauskas, M.E., D.R. Legates, and J. Kastens. 2001. Harmonic analysis of time-series AVHRR NDVI data. Photogrammetric Engineering and Remote Sensing. 67(4):461-470.

[6] Leopold, A. (1933). Game Management. Charles Scribners, New York.

[7] Despain, D. (1990). Yellowstone Vegetation: Consequences of Environment and History in a Natural Setting. Roberts Rinehart Publishers, Santa Barbara.

[8] Cohen, W. B., and T. A. Spies. 1992. Estimating Structural Attributes of Douglas-Fir/Western Hemlock Forest Stands from Landsat and SPOT Imagery. Remote Sensing of Environment. 41(1):1-17.

[9] Running, S. W., Peterson, D. L., Spanner, M. A., and Teuber, K. 1986. Remote Sensing of coniferous forest leaf area. Ecology. 67(1): 273-276.

[10] Moskal, L.M. and M. E. Jakubauskas. (2001). Discriminating forest stand age classes using 2nd order image texture in the Central Plateau of Yellowstone National Park. Proceedings of: 3rd International Forestry and Agriculture Remote Sensing Conference and Exhibition. Denver, CO, November 2001.

[11] Gutman, G., Tarpley, D., and A. Ignatov, 1995. The Enhanced NOAA Global Land Dataset from the Advanced Very High Resolution Radiometer . Bulletin of the American Meteorological Society. 76 (7): 1141-1156.

[12] Jakubauskas, M.E. (1996). Thematic Mapper characterization of lodgepole pine seral stages in Yellowstone National Park, USA. Remote Sensing of Environment. 56:118-132.



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