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Perspectives on monitoring gradual change across the continuity of Landsat sensors using time-series data

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ABSTRACT

There are many types of changes occurring over the Earth's landscapes that can be detected and monitored using Landsat data. Here we focus on monitoring "within-state," gradual changes in vegetation in contrast with traditional monitoring of "abrupt" land-cover conversions. Gradual changes result from a variety of processes, such as vegetation growth and succession, damage from insects and disease, responses to shifts in climate, and other factors. Despite the prevalence of gradual changes across the landscape, they are largely ignored by the remote sensing community. Gradual changes are best characterized and monitored using time-series analysis, and with the successful launch of Landsat 8 we now have appreciable data continuity that extends the Landsat legacy across the previous 43 years. In this study, we conducted three related analyses: (1) comparison of spectral values acquired by Landsats 7 and 8, separated by eight days, to ensure compatibility for time-series evaluation; (2) tracking of multitemporal signatures for different change processes across Landsat 5, 7, and 8 sensors using anniversary-date imagery; and (3) tracking the same type of processes using all available acquisitions. In this investigation, we found that data representing natural vegetation from Landsats 5, 7, and 8 were comparable and did not indicate a need for major modification prior to use for long-term monitoring. Analyses using anniversary-date imagery can be very effective for assessing long term patterns and trends occurring across the landscape, and are especially good for providing insights regarding trends related to long-term and continuous trends of growth or decline. We found that use of all available data provided a much more comprehensive level of understanding of the trends occurring, providing information about rate, duration, and intra- and inter-annual variability that could not be readily gleaned from the anniversary date analyses. We observed that using all available clear Landsat 5–8 observations with the new Continuous Change Detection and Classification (CCDC) algorithm was very effective for illuminating vegetation trends. There are a number of potential challenges for assessing gradual changes, including atmospheric impacts, algorithm development and visualization of the changes. One of the biggest challenges for studying gradual change will be the lack of appropriate data for validating results and products.

1. Introduction

The Landsat series of satellites has enabled the characterization of the Earth's surface since 1972. The more than 33 years of data provided by Landsats 4 through 8 have proven especially well-suited for land characterization activities, owing in large part to the spatial, spectral, and radiometric qualities of the data (Wulder et al., 2008). One common theme that has emerged through the many Landsat data analyses that have been conducted is that the Earth's surface is constantly changing and that the types, magnitudes, rates, and aerial extents of the changes vary markedly from location to location and epoch to epoch. These changes, and the many agents that cause them, are of interest to a large community of scientists and managers who use the information for an array of applications, including assessing effects of global change on biodiversity, carbon cycling, fire fuels, crop types and yields, and hydrology, among others. Another common theme emerging from these analyses is that there is a constant need for current information on land cover and condition for assessing the impacts of the wide array of changes taking place across the Earth's landscapes.

The changes that scientists and natural resource managers are interested in monitoring can be summarized as abrupt change, seasonal change, ephemeral change, and gradual change (Verbesselt, Hyndman, Newnham, & Culvenor, 2010). Abrupt changes are often associated with major alterations in land cover, such as forest harvest, urban development, and wildfire, and most land-change assessments conducted over large areas using medium spatial resolution data have focused on abrupt changes (Hansen & Loveland, 2012). Seasonal changes are related to the phenological cycles of vegetation green-up and senescence and to other temporal

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Table 1
Examples of types of gradual change and the users of such information.

Gradual change	Examples	Example stakeholders	Event duration	References
Disturbance from pest infestations	Mountain pine beetle[1] or western spruce budworm	Foresters	Several years	Meddens, Hicke, Vierling, and Hudak (2013), Liang, Chen, Hawbaker, Zhu, and Gong (2014), Vogelmann, Tolk, and Zhu (2009)
Climate-induced die-off	Climate-induced die-off in pinyon-juniper and aspen in southwestern US	Climate change community	Decades	Yang, Weisberg, and Bristow (2012), Huang and Anderegg (2012);
Shifts in phenological cycles	Longer growing seasons in Arctic	Climate change community	Decades or more	Zeng, Jia, and Forbes (2013), Hamunyela, Verbesselt, Roerink, and Herold (2013);
Forest growth and succession	Succession after harvesting	Carbon community	Several years to decades or more	Czerwinski, King, and Mitchell (2014), Gomez, White, and Wulder (2011)
Invasive species	Cheatgrass and buffle grass	Range biologists, conservation groups	Several years to decades or more	Clinton et al. (2010), Marshall, Lewis, and Ostendorf (2014)
Biome shifts	Vegetation changes at tree lines in mountains	Climate change community	Decades to centuries	Mathisen, Mikheeva, Tutubalina, Aune, and Hofgaard (2014), Beckage et al. (2008)
Shifting patterns of agriculture[1]	Increases in specific crops related to the ethanol industry	Commodity industry	Several years	Rudorff et al. (2010), Brown and Pervez (2014)
Wetland changes	Cyclical climate effects on water levels in North American Prairie Pothole region	Wetland ecologists	Several years or more	Klemas (2011), Moser, Voigt, Schoepfer, and Palmer (2014), Gomez-Rodriguez, Bustamante, and Diaz-Paniqgua (2010)
Gradual impacts from pollution	Forest die-back; Water quality	Foresters, water quality managers	Years to decades	Tote, Delalieux, Goossens, Williamson, and Swinnen (2014), Bresciani, Stroppiana, Odermatt, Morabito, and Giardino (2011)
Overgrazing	Overgrazing in grass and shrub ecosystems	Rangeland managers	Several years	Liu et al. (2013), Wylie, Boyte, and Major (2012)
Desertification and recovery processes	Degradation and greening in the Sahel	Global change community, pastoralists	Years to decades or more	Dardel et al. (2014), Albalawi and Kumar (2013)

[1] These types of gradual change are principally observable at scales broader than the individual pixel.

responses associated with annual cycles of day length, solar angle, and related climatic characteristics. Although seasonal changes are more noticeable in particular regions or biomes, such as areas of deciduous forests and grasslands, these cycles are characteristic of most vegetated areas of the Earth to some degree. Ephemeral changes represent temporary interruptions in the usual energy responses from the landscape, such as from flooding, short term defoliators, or short-term drought (e.g., duration of one or two years). Gradual changes relate to "within-state" (i.e., within land-cover type) shifts in energy response, often with regard to vegetation communities, that are not related to normal phenological cycles (although persistent shifts in phenological responses can constitute gradual change). Gradual changes result from a variety of processes, such as damage to vegetation from insects and disease, vegetation growth and succession, vegetative decline from prolonged drought or air pollution, shrinking of glaciers and polar ice caps, long-term drying of lake beds, sea level rise along shorelines, and many others.

The landscape is constantly changing and many of the changes are gradual. Indeed, it may be the exception when a landscape remains static. Despite the pervasiveness and impacts of gradual change across our landscapes, systematic monitoring and assessment of gradual forms of change have been rarely pursued with mid-resolution or fine-scaled satellite sensors. The four-decade depth of the Landsat data archive offers a wealth of information for characterizing gradual change, but until recently it has been challenging to assemble appropriate time-series data to support the needed analyses. Our main objective in this paper is to draw attention to gradual change. We describe the role of remote sensing for assessing gradual change. We discuss types of change that are important to characterize, how such changes could be characterized, potential difficulties in characterizing gradual change, and future considerations. We include examples of locations undergoing different types of gradual change to facilitate discussion in the science community.

2. Types and characteristics of gradual change

For the most part, we consider gradual changes to be those that are occurring over a period of several years or more, usually involving gradual spectral transitions over that time period. Conceptually, some of the most straightforward cases of gradual change relate to landscapes undergoing a systematic shift through time, such as increasing biomass associated with plant succession and growth, decreasing biomass associated with some particular stress agents, or gradual shifts in species composition related to a number of potential factors. There are many other types of gradual changes and users of such information (Table 1). Depending on the cause, such changes can occur over several years to several decades or longer (Table 1). Unlike abrupt changes, which can often be readily detected using two images (a "before" and "after" image pair), gradual changes are often overlooked or ignored, in part because they are not observable as distinct patterns with well-defined boundaries in the imagery and require analyses of a series of images to have confidence that a change actually has occurred. It is worth noting that most of the examples of gradual change listed in Table 1 are observable at the pixel level. However, the effects of mountain pine beetle infestation and shifting patterns of agriculture may be fundamentally different in that the gradual change occurs at a broader scale (forest stand and agricultural region, respectively). Cumulative effects from ephemeral phenomena could perhaps be included in the list, and similarly may best be assessed using analyses at the landscape level. Regardless, all of these types of gradual changes generally tend to be best characterized through the analysis of time-series data.

It is worthwhile to provide examples of what we do not consider to be a gradual change. Most major and readily discernable land-cover changes, such as forest harvest and urbanization, are not considered to be gradual change. We also do not include annual green-up and senescence cycles (i.e., those associated with plant phenology). However, if the phenological cycle is shifting through time (e.g., lengthening of the growing season), then that would be gradual change. Events that occur over very short duration, such as associated with fires, storms, floods, tornadoes, or other disasters, are certainly not gradual changes, although they may represent intra-state changes. This is because these changes occur in response to a punctuated event that results in an "abrupt change." However, the long-term recovery from these events could be considered as gradual change. It is also worthwhile to make a distinction between "gradual change" and "subtle change." Subtle changes are very difficult to detect, often because the spectral responses