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Scaling effects on spring phenology detections from MODIS data at multiple spatial resolutions over the contiguous United States

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A B S T R A C T

Land surface phenology (LSP) has been widely retrieved from satellite data at multiple spatial resolutions, but the spatial scaling effects on LSP detection are poorly understood. In this study, we collected enhanced vegetation index (EVI, 250 m) from collection 6 MOD13Q1 product over the contiguous United States (CONUS) in 2007 and 2008, and generated a set of multiple spatial resolution EVI data by resampling 250 m to 2 × 250 m and 3 × 250 m, 4 × 250 m, ..., 35 × 250 m. These EVI time series were then used to detect the start of spring season (SOS) at various spatial resolutions. Further the SOS variation across scales was examined at each coarse resolution grid (35 × 250 m ≈ 8 km, refer to as reference grid) and ecoregion. Finally, the SOS scaling effects were associated with landscape fragment, proportion of primary land cover type, and spatial variability of seasonal greenness variation within each reference grid. The results revealed the influences of satellite spatial resolutions on SOS retrievals and the related impact factors. Specifically, SOS significantly varied lineally or logarithmically across scales although the relationship could be either positive or negative. The overall SOS values averaged from spatial resolutions between 250 m and 35 × 250 m at large ecosystem regions were generally similar with a difference less than 5 days, while the SOS values within the reference grid could differ greatly in some local areas. Moreover, the standard deviation of SOS across scales in the reference grid was less than 5 days in more than 70% of area over the CONUS, which was smaller in northeastern than in southern and western regions. The SOS scaling effect was significantly associated with heterogeneity of vegetation properties characterized using land landscape fragment, proportion of primary land cover type, and spatial variability of seasonal greenness variation, but the latter was the most important impact factor.

1. Introduction

Plant phenology, especially spring phenology, has been reported as one of the most effective indicators of climate change (Badeck et al., 2004; Friedl et al., 2006; Parmesan, 2006; White et al., 2009; Ma et al., 2013; IPCC 2007; Xin, 2016; Melaas et al., 2016), and it is also linked to the primary productivity, crop yield, insect emergence, and bird migration (Parmesan, 2006; Ault et al., 2015; Xin, 2016). The start of spring season (SOS) has been widely measured from ground observations and satellite-derived vegetation greenness. The ground observations, including the field observations (such as USA-National Phenology Network), canopy cameras measurements (such as PhenoCam) (Denny et al., 2014; Klosterman et al., 2014; USA National Phenology Network, 2015; Brown et al., 2016), generally provide limited samples of phenological variants in individual species and local vegetation community. In contrast, satellite remote sensing has the significant advantage of monitoring SOS in a synoptic landscape coverage with repeated temporal sampling at regional to global scales (Myneni et al., 1997; Zhang et al., 2003; White et al., 2009; Delbart et al., 2015; Wu et al., 2016).

Remotely sensed data from different satellite platforms or sensors have been frequently used to produce land surface phenology

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(LSP) products over the past several decades (Goward et al., 1985; Zhang et al., 2003; Delbart et al., 2006; Piao et al., 2006; Dash et al., 2010; Ganguly et al., 2010; Shen et al., 2014). The commonly used vegetation indices (VIs) for land surface phenology detection are the normalized difference vegetation index (NDVI, Tucker and Sellers, 1986) and enhanced vegetation index (EVI, Huete et al., 2002). The VIs seasonal variation from different sensors characterizes phenological properties across multiple spatial resolutions, such as 30 m Landsat Thematic Mapper (or Enhanced Thematic Mapper) images, 300 m Medium Resolution Imaging Spectrometer (MERIS) data, MODerate-resolution Imaging Spectroradiometer (MODIS) data with the spatial resolutions of 250 m, 500 m, 1000 m, and 0.05 deg, Advanced Very High Resolution Radiometer (AVHRR) images from 1.1 km to 8 km [such as GIMMS (global inventory modeling and mapping studies) NDVI], and 1 km SPOT (Systeme Probatoire d'Observation de la Terre) vegetation NDVI data (Zhang et al., 2003; Fisher et al., 2006; White et al., 2009; Ganguly et al., 2010; Dash et al., 2010; Guyon et al., 2011; Xin et al., 2015). Fine spatial resolution data characterize vegetation seasonality and phenology properties for individual vegetation types at a field scale (such as 30 m); whereas coarse spatial resolution data quantify seasonal greenness dynamics at a landscape scale containing various vegetation types and phenological properties (Zhang et al., 2017). This means vegetation phenology could diverge considerably among plant species within a local area or satellite footprint (Piao et al., 2007; Zhang and Goldberg, 2011; Mazer et al., 2015; Piao et al., 2015; Delbart et al., 2015; Wu et al., 2016). For example, the SOS for different vegetation types (crop and natural vegetation) within a 500 m heterogeneous pixel could vary more than three months (Fisher et al., 2006; Zhang et al., 2017a). However, current satellite remote sensing at regional and global scales has the capability of detecting phenology of vegetation communities at a pixel footprint coarser than 250 m (commonly from 250m to 8 km). On the other hand, environmental modeling, climate change analyses, and ecological monitoring are mainly based on coarse resolution phenology data (Myneni et al., 1997; Badeck et al., 2004; Allstadt et al., 2015; Piao et al., 2015). Therefore, our question is whether the SOS detected from coarse satellite data could represent overall phenology properties at relatively finer resolutions by investigating the scaling effects of SOS derived from 250 m to 8 km satellite data.

In this study, we collected vegetation indices from MODIS data and detected LSP SOS across multiple spatial resolutions from 250 m to 8 km over the contiguous United States (CONUS) to investigate the SOS scaling effects. Our specific goals are to (1) examine SOS variations with the changes of spatial resolutions, (2) investigate the spatial patterns of satellite scale effects on SOS across ecoregions, and (3) explore the factors influencing SOS scaling effects.

2. Materials and methods

2.1. Data

MOD13Q1 data (Collection 6) in 2007 and 2008 were acquired from NASA (ftp://ladsweb.nascom.nasa.gov/allData/6/). MOD13Q1 is produced every 16 days at a 250 m spatial resolution as a gridded level-3 product with the sinusoidal projection. The MOD13Q1 Collection 6 algorithm calculates vegetation indices from pre-composited (8-day) surface reflectance data that are filtered based on quality, cloud, and viewing geometry (Didan et al., 2015). The best quality pixel represents a cloud-free and nadir view observation without residual atmospheric contamination while lower quality pixels are cloud-contaminated with extreme off-nadir sensor views. The 16-day vegetation indices are generated using an algorithm of Constrained View angle – Maximum Value Composite (CV-MVC) (Huete et al., 2002; Jiang et al., 2008; Didan, 2015). The surface reflectance in the MOD13Q1 employs a minimum blue band approach to minimize aerosols and other contaminants (Huete et al., 2002; Jiang et al., 2008; Didan, 2015). From MOD13Q1 product, we extracted EVI and the reflectance in blue, red, and near-infrared (NIR), as well as the Quality Assessment (QA) information for land surface phenology detection (Section 2.2). The selection of EVI is due to the fact that EVI is sensitive to greenness variation over high biomass regions and insensitive to the canopy background signal and atmosphere influences (Huete et al., 2002; Jiang et al., 2008).

MODIS land cover type was collected to examine the influence of spatial heterogeneity of vegetation patterns on SOS retrievals. MODIS land cover product (MCD12Q1) is produced using a supervised classification algorithm based on high-quality land cover training sites, which was developed using Landsat or SPOT digital imagery in conjunction with ancillary data (Muchoney et al., 1999). The primary land cover classification scheme is provided by an International Geosphere-Biosphere Program (IGBP) (Friedl et al., 2010). This study used the most recent version of the MODIS land cover type product at a spatial resolution of 500 m in 2007, and was resampled to the same spatial resolution of MOD13Q1 (i.e. 250 m).

Ecoregions over the CONUS were obtained from the Forest & Rangeland Ecosystem Science Center for the investigation of SOS dependences on ecosystems. This data set shows ecoregions in four levels (Bailey, 1995, 2004; Omernik and Bailey, 1997). The largest ecosystem is domains and then followed by divisions within the domains, which is differentiated based on precipitation levels and temperature patterns. Divisions are subdivided into provinces based on vegetation or other natural land covers. The finest level is called sections, which are subdivisions of provinces based on terrain features. In this study, we conducted studies at the division level after merging several close divisions to six new divisions as shown in Fig. 1.

2.2. SOS detection from MODIS EVI time series

To explore the scaling effects of SOS detections, we firstly generated 16-day EVI time series at 35 levels of spatial resolutions in 2007 and 2008. Specifically, the EVI data were aggregated from 250 m MOD13Q1 EVI to 2×250 m, 3×250 m, 4×250 m, ... 35×250 m by averaging good quality observations. The EVI quality was provided in MOD13Q1 QA in which the pixels contaminated by clouds, aerosols, and other contaminants are endowed as low quality. The coarsest spatial resolution aggregated in this study was 35×250 m ($\sim$8 km) that corresponds to the spatial resolution of AVHRR images, particularly GIMMS NDVI3g, which were widely used for long-term phenology analyses (Zhou et al., 2001; White et al., 2009; Julien and Sobrino, 2009; Zhang et al., 2007; de Jong et al., 2011). This resolution is also the coarsest in currently available land surface phenology products. Thus, the resolution of 35×250 m ($\sim$8 km) is called the reference grid hereafter.

In this study, we generated multiple spatial resolution EVI data from MODIS 250m EVI using an average approach. Theoretically, linearity in the composition of the surface components in a pixel is strictly valid only for the original spectral reflectance (Lobell and Asner, 2004). However, previous studies indicate that the linearity assumption of vegetation indices only leads to a very minor inaccuracy (Busetto et al., 2008; Kerdiles and Grondona, 1995; Zhang and Goldberg, 2011). We were aware of the theoretical nonlinearity of the EVI within a pixel, so that we compared the $\sim$8 km EVI dataset aggregated from 250 m EVI with that calculated from $\sim$8 km reflectance that was resampled from 250 m MOD13Q1 products in 2007. It was found that the difference between the