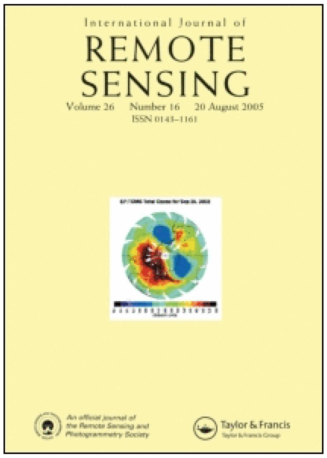


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P. S. A. Beck [ab]; T. J. Wang [b]; A. K. Skidmore [b]; X. H. Liu [c]
[a] NORUT IT AS, N-9291 TromsØ, Norway
[b] International Institute for Geo-Information Science and Earth Observation (ITC), 7500 AA Enschede, The Netherlands
[c] Department of Environmental Science and Engineering, Tsinghua University, Beijing 100084, China

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**Letter**

# Displaying remotely sensed vegetation dynamics along natural gradients for ecological studies

P. S. A. BECK*†‡, T. J. WANG‡, A. K. SKIDMORE‡ and X. H. LIU§
†NORUT IT AS, N-9291 Tromsø, Norway
‡International Institute for Geo-Information Science and Earth Observation (ITC), PO Box 6, 7500 AA Enschede, The Netherlands
§Department of Environmental Science and Engineering, Tsinghua University, Beijing 100084, China

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Normalized difference vegetation index (NDVI) datasets are growing in popularity to represent vegetation dynamics in ecological studies. Because of its multidimensional nature, it is difficult to visualise the spatial and temporal components of NDVI datasets simultaneously. This letter presents a method to display vegetation dynamics as captured by the NDVI along natural gradients and to visualise and test correlations between vegetation phenology and animal movement.

## 1. Introduction

Remote sensing data are increasingly being used for ecological studies (Pettorelli *et al.* 2005). The normalized difference vegetation index (NDVI), in particular, is useful because it shows spatial and temporal trends in vegetation dynamics, productivity and distribution (Reed *et al.* 1994, Nemani *et al.* 2003). Consequently, the NDVI is growing in popularity as a tool to investigate the interaction between vegetation and animal activity, including migration (Boone *et al.* 2006, Ito *et al.* 2006).

Until this century, the AVHRR and SPOT sensors were the only instruments providing data to construct NDVI time series at an almost-daily resolution. The 1 km spatial resolution of these datasets limits their applicability for all but continental and global ecological studies. Now, however, MODIS and MERIS data can be used to produce NDVI time series of almost-daily resolution at a spatial resolution as high as 250 or 300 m, making them useful for local and regional studies. Derived datasets for monitoring regional vegetation activity, for example, may be validated with *in situ* observations of vegetation phenology (Delbart *et al.* 2006, Beck *et al.* 2007). Hence, time series are well suited to represent the dynamics of vegetation activity in ecological studies, and compare them, for example, to animal migration and movement.

Displaying NDVI time series and relating them to ecological phenomena is challenging, as the datasets are typically multidimensional, quantifying vegetation activity in space, as well as through time. The most common approach is to exclude either the spatial or the temporal component of the data in the visualisation. A single time series of the NDVI may, for example, be shown to exemplify the data

*Corresponding author. Email: beck@itc.nl

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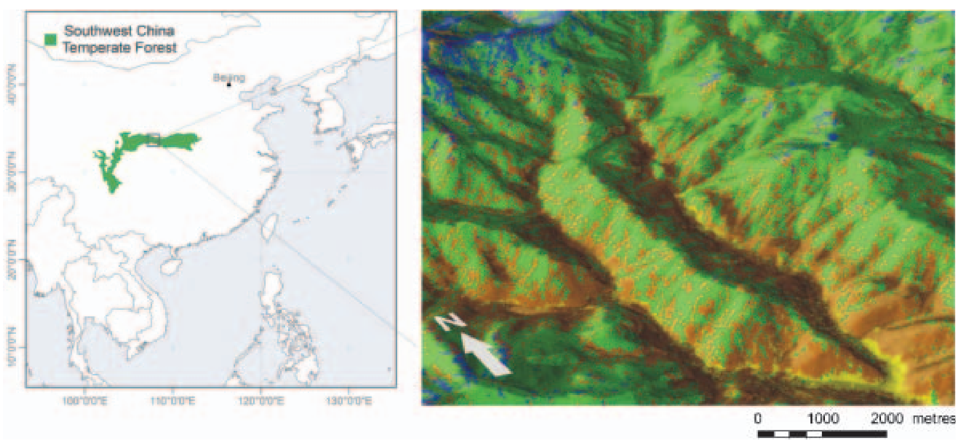
(e.g. Stöckli and Vidale 2004), or a map depicting a 'time-slice' of the data may represent the NDVI in space at a given moment in time (e.g. Pettorelli *et al.* 2005). Alternatively, a parameter derived from the NDVI time series, such as a principal component or the estimated start of the growing season, may be mapped (e.g. Naizot *et al.* 2004, Karlsen *et al.* 2007) or plotted against a geographical gradient (e.g. Zhang *et al.* 2003). While these approaches are complementary, none represents the temporal and spatial patterns in an NDVI dataset simultaneously.

Since its first use, colour palettes have been applied to map the NDVI. Occasionally, colour palettes have been used to represent NDVI values along axes other than a geographical grid: Stöckli and Vidale (2004) displayed the NDVI along a time axis with daily resolution and a range of 1 year versus an axis with yearly resolution. This allowed them to display interannual and seasonal variability in the NDVI and the start and end of the growing season in a single figure. Dye and Tucker (2003) displayed annual vegetation index (VI) patterns in colour along a latitudinal gradient and Anyamba and Tucker (2005) displayed them along a longitudinal gradient. In these latter two examples, colour bars represent the annual trajectory of the NDVI in a single stratum of, respectively, latitude and longitude.

Here, the method of displaying NDVI along spatial and temporal dimensions simultaneously is developed further. It is applied to a mountainous area to show how the vegetation greenness changes in time and with altitude. Using the movement data of radiotracked giant pandas in the area in addition illustrates how the display method facilitates visualising correlations between vegetation phenology and other biotic factors, in this case seasonal animal movement.

## 2. Study area and MODIS NDVI data

The Foping Biosphere Reserve is located in southwestern China and between altitudes of 1000 and 2900 m (see figure 1). The area is mostly forested with understorey vegetation dominated by bamboo species and has the highest




(*a*) (*b*)

Figure 1. (*a*) The location of Foping Biosphere Reserve and the southwest China temperate forest it is a part of, in eastern Asia. (*b*) A vegetation map of Foping Biosphere Reserve (Liu 2001), overlaid on a digital elevation model with a 30 m horizontal resolution. Deciduous broadleaf forest is shown in brown, mixed forest in green, evergreen coniferous forest and bamboo meadows in blue and other land cover types yellow.

population density of giant pandas in the world (State Forestry Administration 2006).

MODIS NDVI data (MOD13) over part of the Foping Biosphere Reserve were downloaded. The dataset provides 23 NDVI images per year at 16 day interval, where every pixel value is the product of maximum value compositing (Huete *et al.* 2002). From the 5 year data between 2001 and 2005, the best 1 year time series, consisting of 23 images, was composed as follows: for each pixel and compositing period, the five available NDVI values were extracted and the mean of the three values of highest quality was calculated. If more than three values had the highest quality, the mean NDVI of all these was used. The quality judgement was based on the usefulness index accompanying the MODIS data.

To interpolate the 23 values of the average NDVI time series for display purposes and to reduce noise in the data, the TIMESAT software package and a Savitsky–Golay function were used (Jönsson and Eklundh 2004).

## 3. Relative phenological development (RPD)

Changes in NDVI through time reflect phenological development in terrestrial vegetation types ranging from the Arctic to the tropics (Krishnaswamy *et al.* 2004, Beck *et al.* 2006). The interpolated NDVI trajectory of each pixel was normalized to cover the range of 0% to 100%, indicating the minimum and maximum NDVI for a given pixel, respectively. Therefore, $RPD_t=(NDVI_t–NDVI_{min})/(NDVI_{max}–NDVI_{min})$, where $NDVI_{min}$ is the minimum NDVI for the pixel, $NDVI_{max}$ is the maximum NDVI for the pixel and $RPD_t$ and $NDVI_t$ are the relative phenological development at and NDVI at time $t$, respectively.

Thus, when viewing the RPD of two pixels at a given time $t$, one can compare the state of greenness of the two pixels irrespective of their absolute NDVI values. Here, this scale is termed the relative phenological development (RPD).

## 4. Giant panda movement data

The giant panda movement data were gathered between June 1991 and December 1995 from three female and three male individuals equipped with radiocollars. The geographical position of the animals was estimated from at least three bearings recorded in the field. As successful registration was not possible every day and for every animal, the number of position estimates varied between animals, from 107 to 465, with a mean of 293.

The first MODIS sensor was launched in 1999, while the giant panda movement datasets are from 1991 to 1995. It was tested whether the 2001 to 2005 average NDVI time series may represent the period 1991 to 1995 by comparing the temperature and precipitation in the two periods, as these are main drivers of plant phenology (Cleland *et al.* 2007).

## 5. Compatibility of the NDVI and giant panda movement data

In general, the 1991 to 1995 period is comparable to the 2001 to 2005 period, although the mean monthly temperature was slightly higher than the 2001 to 2005 maximum in August, November and December (figure 2(*a*)). The difference was greatest in November, where the 1991 to 1995 mean was 0.9 °C warmer than the 2001 to 2005 maximum. The mean monthly precipitation in the 1991 to 1995 period was 10 mm higher than the 2001 to 2005 maximum in April and 40 mm lower than

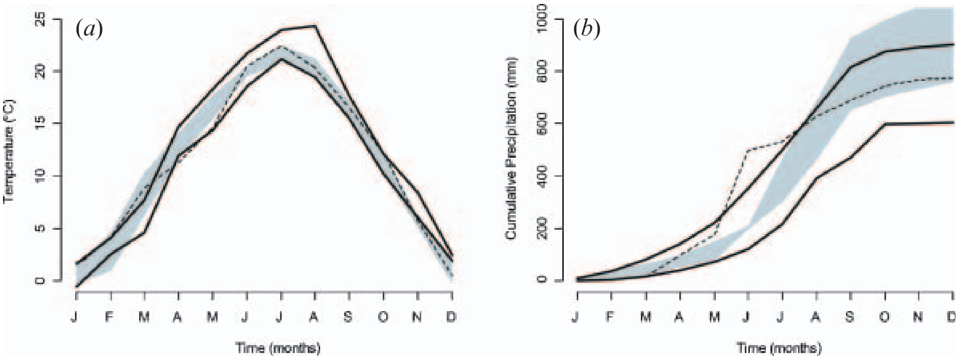



Figure 2. Range of (*a*) monthly temperatures and (*b*) cumulative precipitation in Foping from 1991 to 1995, when giant panda location data were collected (lines), and from 2001 to 2005, when MODIS NDVI data were collected (shaded area, excluding 2002). The year 2002 (dashed line) was unusual, because it saw very high rainfall (210 mm) on 9 June. The meteorological station was moved to a new location in July 2001. Therefore, all temperature recordings from this date onwards were adjusted downwards to correct for the 260 m difference in altitude of the two locations, assuming a lapse rate of 6.5 °C/km.

the 2001 to 2005 minimum in September and the driest summers occurred in the former period (figure 2(*b*)). Overall, the climate in the period with NDVI observations was somewhat colder in summer and autumn than in the period with giant pandas, and also slightly wetter. The year 2002 was unusual as it saw 210 mm of rainfall on 9 June (Hou *et al.* 2006). However, when excluding the year 2002 from the NDVI data composition as described in §2, the average NDVI values for the 23 images did not change by more than 0.02. Hence, the NDVI is generally representative of the years with giant panda observations.

## 6. Visualisation

Vegetation activity, estimated using the NDVI time series, was displayed in the Foping Biosphere Reserve along an altitudinal gradient. Annual NDVI trajectories were stratified by altitude and plotted along axes of time and altitude (figure 3(*a*)). To facilitate the comparison of phenological development at different altitudes and across vegetation types, the plot was coloured according to the RPD. Thus, bands of similar colour in the figure can be regarded as vegetation in similar phenological stages, allowing for differences between vegetation types, because of the normalization in the RPD calculation (for non-normalized phenological indices, see Krishnaswamy *et al.* (2004) and Das *et al.* (2006). The figure clearly shows how the period of dormancy lengthens and the growing season shortens towards higher altitudes; at the lowest altitudes, the dormancy period continues until April, while it continues until May at the highest altitudes. This concurs with the ground observations of Wang *et al.* (in press) that in the Foping Biosphere Reserve, canopy trees leaf out in mid April to late May and leaf fall is complete by mid October to early November. After dormancy, the vegetation reaches maximum greenness in the course of about 1 month at the lowest altitudes, increasing to almost 2 months on the mountain peaks. In the middle of summer and the middle of winter, the average NDVI in the area is constant across the altitude gradient in the area. The length of near-maximum greenness lasts for more than 4 months in the lowlands, but for only 3 months on the mountain plateaus and tops.

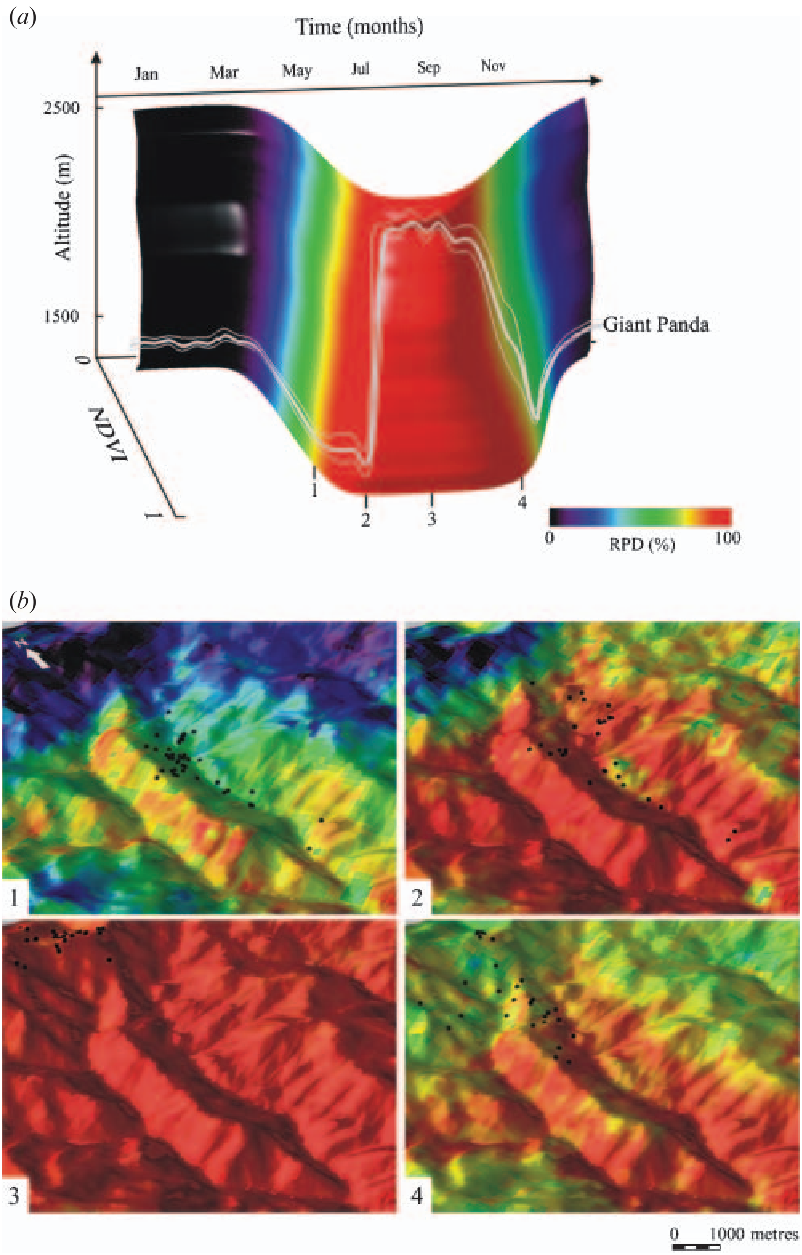



Figure 3. (*a*) Summarized phenology of the Foping biosphere reserve as detected by MODIS NDVI after processing with TIMESAT. The RPD is a rescaled version of the NDVI. The solid white line shows the average altitudinal movement of six radiotracked giant pandas and the thin white lines indicate the standard error of the average. (*b*) Time-slices of RPD during early spring, late spring, summer and early autumn, with the positions of the radiotracked giant pandas during a 10 day period indicated by black dots.

The altitudinal movement of the giant pandas in the area shows a striking correlation with the phenological development of the area. In spring, the animals move rapidly to higher altitudes when the vegetation reaches its peak greenness. In autumn, the gradual movement of the animals to lower altitudes coincides with the onset of vegetation senescence from the highlands to the valleys.

In addition, the RPD was mapped during early spring, late spring, summer and early autumn and showed the giant panda locations in the corresponding periods (figure 3(*b*)). The maps were overlaid on a shaded digital elevation model of the area. Together, they further illustrate how the phenological development correlates with altitude and strongly indicate that phenological development drives the giant panda movement. The display methods described here provide a useful exploratory tool when relating vegetation activity, as monitored in remote sensing, to other ecological phenomena.

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