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Using the satellite-derived NDVI to assess ecological responses to environmental change

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Assessing how environmental changes affect the distribution and dynamics of vegetation and animal populations is becoming increasingly important for terrestrial ecologists to enable better predictions of the effects of global warming, biodiversity reduction or habitat degradation. The ability to predict ecological responses has often been hampered by our rather limited understanding of trophic interactions. Indeed, it has proven difficult to discern direct and indirect effects of environmental change on animal populations owing to limited information about vegetation at large temporal and spatial scales. The rapidly increasing use of the Normalized Difference Vegetation Index (NDVI) in ecological studies has recently changed this situation. Here, we review the use of the NDVI in recent ecological studies and outline its possible key role in future research of environmental change in an ecosystem context.

Studying ecosystem responses to increased surface temperature over the Northern hemisphere is a major focus of the scientific community [1,2]. Moreover, human activity has profoundly affected ecosystems (e.g. via habitat destruction and biodiversity reduction) so that the need to detect and predict changes in ecosystem functioning has never been greater [3]. Field data currently available are generally difficult to use for predicting regional or global changes because such data are traditionally collected at small spatial and temporal scales and vary in their type and reliability. Satellite imagery has become a potential 'goldmine' for ecologists in that context, as recently underlined by Kerr and Ostrovsky [4], and Turner *et al.* [5].

Of the information that can be derived from the satellite-collected data (e.g. sea surface temperature, ocean colour, and topography [5]), data on phenology, and the amount and distribution of vegetation are of prime importance for terrestrial ecologists because vegetation strongly influences animal distributions and dynamics.

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Recent ecological studies have highlighted the relevance of the Normalised Difference Vegetation Index (NDVI; see Glossary) as an index linking vegetation to animal performance. The NDVI [6,7] is derived from the red: near-infrared reflectance ratio [$\mathrm{NDVI}=(\mathrm{NIR}-\mathrm{RED})/(\mathrm{NIR}+\mathrm{RED})$, where NIR and RED are the amounts of near-infrared and red light, respectively, reflected by the vegetation and captured by the sensor of the satellite]. The formula is based on the fact that chlorophyll absorbs RED whereas the mesophyll leaf structure scatters NIR. NDVI values thus range from -1 to $+1$, where negative values correspond to an absence of vegetation [7].

The relationship between the NDVI and vegetation productivity is well established, and the link between this index and the fraction of absorbed photosynthetic active radiation intercepted (fAPAR) has been well documented, theoretically [8] and empirically [9]. Moreover, direct effects of climatic conditions on biomass and phenological patterns of vegetation as assessed by the use of the NDVI have been reported for many ecosystems [10–15], as have the feedback effects of vegetation on local climate [16,17].

Different NDVI data sets are available, with different spatial and temporal resolutions, and different temporal coverage (Box 1 [4,5]). We broadly distinguish:

- The long-term NDVI data sets, including (i) the coarse scale (8–16 km resolution) National Oceanic and Atmospheric Administration–Advanced Very High Resolution Radiometer (NOAA–AVHRR) time-series extending from 1981 to the present (Box 1); and (ii) the small-scale (few meters) Landsat–Thematic Mapper (TM) data set extending from 1984 to 2003; and
- The better quality, but short-term NDVI time-series, including (i) the Moderate Resolution Imaging Spectroradiometer (MODIS–TERRA) data set (250–1000 m resolution) extending from 2000 to the present, and (ii) the Satellite Pour l'Observation de la Terre–Vegetation (SPOT–VGT) data (up to a few meters resolution) extending from 1998 to the present.

Here, we review recent ecological studies that have successfully used the NDVI to gain novel insight into direct and indirect effects of environmental change. We

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Glossary

AVHRR: Advanced Very High Resolution Radiometer.
BISE: Best Index Slope Extraction. This is a method aiming at smoothing NDVI time-series.
BRDF: Bidirectional Reflectance Distribution Function. This gives the reflectance of a target as a function of illumination geometry and viewing geometry. The BRDF depends on wavelength and is determined by the structural and optical properties of the surface, such as shadow-casting, mutiple scattering, mutual shadowing, transmission, reflection, absorption and emission by surface elements, facet orientation distribution and facet density.
DAAC: Distributed Active Archive Centre.
Drop-out: these are data missing from a satellite image. Drop-outs can be caused by signal interference or sensor failure.
EVI: Enhanced Vegetation Index. This is an 'optimized' index designed to enhance the vegetation signal with improved sensitivity in high biomass regions and improved vegetation monitoring through a decoupling of the canopy background signal and a reduction in atmosphere influences. The equation takes the form EVI = G*(NIR − RED)/(NIR + c1*RED − C2*BLUE + L), where G is the gain factor, BLUE is the blue reflectance, L is the canopy background adjustment that addresses non-linear, differential NIR and red radiant transfer through a canopy, and C1 and C2 are the coefficients of the aerosol resistance term, which uses the blue band to correct for aerosol influences in the red band.
fAPAR: Fraction of Absorbed Photosynthetic Active Radiation; the proportion of incoming solar radiation in the photosynthetically active region of the solar spectrum that is effectively absorbed by plants for photosynthesis.
GAC: Global Area Coverage.
GIMMS: Global Inventory Modelling and mapping studies.
GVI: Global Vegetation Index. See Box 1.
INDVI: Integrative Normalized Difference Vegetation Index; corresponding to the sum of positive NDVI values over a year.
LAI: Leaf Area Index; it is defined as the one-sided green leaf area per unit ground area in broadleaf canopies, or as the projected needleleaf area per unit ground area in needle canopies.
MODIS: The Moderate Resolution Imaging Spectroradiometer.
MVC: Maximum Value Compositing. This is a method aiming at smoothing NDVI time series.
NASA: National Aeronautics and Space Administration.
NDVI: Normalized Difference Vegetation Index; a satellite-based vegetation index that correlates strongly with aboveground net primary productivity.
NIR: Near Infrared Reflectance.
NOAA: National Oceanic and Atmospheric Administration.
PAL: Pathfinder AVHRR Land.
RED: Red reflectance.
SAVI: Soil Adjusted Vegetation Index. It is defined as [(NIR − RED)/(NIR + RED + L)]*(1 + L), where L is a correction factor which ranges from 0 for very high vegetation cover to 1 for very low vegetation cover. The most typically used value is 0.5 which is for intermediate vegetation cover.
SPOT VGT: Satellite Pour l'Observation de le Terre, Vegetation.
TM: Thematic Mapper.

also outline the general workflow in linking the NDVI to biological data by reviewing methods that are available to reduce noise in NDVI time-series (Table 1; Box 2), the pertinent biomass and phenological measures that one can extract from NDVI data (Figure 1; Table 2), and make caveats about the use of NDVI data (Box 3). The NDVI has shown consistent correlation with vegetation biomass and dynamics in various ecosystems worldwide [6,7]. Furthermore, the relationships between the NDVI and climatic variables have been explored to the extent that making predictions is now possible [18–20]. The NDVI thus represents the first useful tool with which to couple climate, vegetation and animal distribution and performance at large spatial and temporal scales.

Using the NDVI to monitor vegetation and plant responses to environmental change

Because the NDVI correlates directly with vegetation productivity [21], there are numerous possible applications of this index for ecological purposes. The NDVI provides information about the spatial and temporal distribution of vegetation communities [21], vegetation biomass [21], CO_2 fluxes [22,23], vegetation quality for herbivores (because the rate of greening can be correlated with food quality [24]) and the extent of land degradation in various ecosystems [25,26].

The NDVI was used originally to generate maps, including the pioneering mapping of vegetation distribution and productivity in Africa [27]. The ecological relevance of such maps is multiple: the NDVI enables us to differentiate ecosystem functional types or biozones [28,29], to quantify the annual net primary productivity (ANPP) at various scales worldwide [6] and to differentiate land cover at the continental [6] and global [30] scales. By using the NDVI, it is possible to differentiate savannah, dense forest, non-forest and agricultural fields (in Africa [31] and in Asia [32]). Phenological characteristics can be used to determine evergreen forest versus seasonal forest types [32,33] or trees versus shrubs [34]. However, differentiating between forests with, for example, different dominant species is not possible using this kind of remote-sensing information, because several assemblages of plant species can produce a similar NDVI value or a similar NDVI temporal trend. Even with data of sufficiently high spectral and spatial resolution, few plant species, if any, can be identified accurately [35].

The NVDI has also been used to improve our predictions and impact assessments of disturbances such as drought [36], fire [37], flood [38] and frost [39]. The use of the NVDI in the monitoring of drought or in the evaluation of dynamic fire risk relies on the sensitivity of the index to vegetation dryness, a major predisposing factor for fire occurrence. For example, using 16 years of data on fire occurrence in Tuscany, Maselli *et al.* reported consistent negative correlations between fire probabilities and standardized NDVI levels of previous or contemporaneous decades [37]. The authors were then able to obtain risk estimates that could be used for operational applications on different spatial scales. The predictive precision achieved was estimated as low at high spatial resolution, but reached intermediate levels on provincial and regional scales [37].

Because water has a much lower NDVI value than do other surface features, inundated areas can also be distinguished by changes in the NDVI value before and after the flood, after eliminating the effects of other factors on the NVDI. This method was used in China to assess flood damage in 1998, and the results showed high correlation with flood damage estimated using other methods [38].

Finally, because vegetation dynamics and local climate are intrinsically linked, vegetation dynamics could provide information about climatic events, such as frosts. In New Zealand, for example, the NVDI was used to explain a significant amount of variation (from 10 to 20%) in the date of the first (the NVDI in autumn) and last (the NVDI in spring) frost, as well as the length of the frost-free period (the NVDI in autumn) [39].

Using the NVDI to assess trophic interactions

So far, the NDVI has been used predominantly in studies focusing on the effects of environmental change on plants.

Box 1. AVHRR data

Since 1994, NDVI data from the AVHRR data set have been made publicly available over the Internet (http://www.noaa.gov). Different AVHRR-based NDVI data sets are also available (Table I), with differences in corrections applied or in the spatial and temporal resolutions available. They are all derived from the 4-km Global Area Coverage (GAC) data collected daily by the NOAA satellites: over the past 20 years, five satellites have been launched and data have been intercalibrated across the NOAA-7, 9, 11 14 and 16 satellites [57].

AVHRR data are an invaluable and irreplaceable archive of historical land surface information and have literally revolutionized vegetation studies. Nowadays, this is the only freely available data set that gives daily coverage over an extensive time period (1981–present), and the data produced by the Global Inventory Modelling and Mapping Studies (GIMMS) group show good correlation with data from higher quality sensors, such as SPOT VGT and MODIS TERRA [58]. Such features of these data should promote their use in ecological studies, particularly, for example, in studies of global climate change.

However, the spatial resolution is coarse, making AVHRR data suitable for regional studies but limiting its usefulness for detailed studies in landscapes with important heterogeneity at finer scales [59]. GAC data are generated by onboard sampling of the full-resolution (1.1 km) data: for a given scan line, the first four pixels out of every five are averaged and only every third scan line is processed. NDVI products are then generated from the GAC data, using the MVC (Table 1, main text) spatial aggregation procedure directly based on the NVDI [58,60] or based on the difference between NIR and RED [61]. This point is of little consequence as long as the resolution of the study objects is greater than that of the cell size of the AVHRR [59].

Finally, the quality of AVHRR data is far lower than the quality of the data collected by MODIS or SPOT VGT: if the biological question requires a smaller spatial resolution and does not need vegetation data before 1998, data from MODIS or SPOT VGT should be used.

Table I. The different NDVI data sets

Data set	Satellite	Instrument	Temporal span	Temporal resolution	Missing data	Range	Website
PAL	NOAA	AVHRR	July 1981–September 2001	1 day, 10-day, monthly, seasonal	September 1994–January 1995	8 km	http://daac.gsfc.nasa.gov/guides/GSFC/guide/avhrr_dataset.gd.html
GVI	NOAA	AVHRR	May 1982–Present	Week, monthly, seasonal	September 1994–January 1995	16 km	http://www2.ncdc.noaa.gov/docs/gviug/index.htm
GIMMS	NOAA	AVHRR	July 1981–Present	Bimonthly index (10-day for Africa)	None	8 km	http://ltpwww.gsfc.nasa.gov/gimms/htdocs/
MOD13	TERRA (EOS AM)	MODIS	February 2000–Present	16 days	None	250 m–1 km	http://modis.gsfc.nasa.gov/
	TM/ETM	Landsat	1984–2003	16 days	None	<1–30 m	http://landsat.usgs.gov/
	VGT	SPOT	April 1998–Present	10 days	None	1 km	http://www.spotimage.fr

However, the NDVI could also be used to gain novel insight into trophic inter-linkages. The use of the NVDI as a covariate rather than as a response variable has opened up new areas of research in trophic interactions. Recently, studies have coupled vegetation dynamics, as assessed by the NVDI, with biodiversity [35,40,41], animal species distribution [42–44], the movement patterns of animals [45,46] and the performance of animal populations [24,47–49]. Examples include the mean arrival date for yearling barn swallows *Hirundo rustica* in Algeria [45] and the expansion rate of roe deer *Capreolus capreolus* populations in Norway [46]. In addition, NDVI-based estimates of productivity in the USA were reported to explain up to 61% of avian species richness [40]. In Eritrea, the home ranges of the grivet monkey *Cercopithecus aethiops* exhibited a significantly higher average NDVI value compared with the average of the survey area [44]. In Mauritania and on the Red Sea coast, high resource abundance, indicated by high NDVI values, was shown to promote locust *Schistocerca gregaria* multiplication, whereas contraction of resources into small patches (reflected by the spatial aggregation of pixels with high NDVI values) increased locust concentration [50]. These results have direct implications for the understanding of the spatial distribution of locust outbreaks [50]. Body mass and calf survival of reindeer *Rangifer tarandus* was shown to be positively correlated with the NVDI in spring [24,48], whereas the timing of the spring vegetation flush, identified from NDVI time-series, and the rutting and calving of red deer *Cervus elaphus* were all found to be later in Norway than in France [51]. For the pied flycatcher *Ficedula hypoleuca*, the NVDI has been successfully linked to breeding success [49]; in barn swallows, it was related to clutch size, breeding date, tail and wing lengths [47].

As demonstrated by the previous examples, NDVI enables ecologists to quantify at various spatial scales how changes in vegetation distribution, phenology and productivity will affect upper trophic levels. This makes it possible, for example, to determine how much of the climatic effects on herbivore behavior, performances and dynamics are operating through the effects of climate on vegetation distribution, phenology and productivity, (i.e. through trophic interactions). Such insight might help in efforts to manage and conserve herbivores and the community associated to their presence efficiently, as one can then target the right factor, if it is feasible to do. To know the actual mechanisms and pathways by which environmental changes affect herbivores will also enable better predictions of further changes. For example, if global warming mainly operates through decreasing snow depth, we are likely to see no further responses to increased temperature once there is no permanent snow cover established. However, if climate operates through plants, detailed knowledge about how plants respond to temperature will enable more robust predictions to future scenarios of environmental change.

Ecologically relevant measures that can be derived from NDVI time-series

It can be complicated to couple information from two trophic levels when each is assessed at different temporal

Table 1. Overview of the main advantages and disadvantages of the principal NDVI smoothers

Procedure	What it does	Advantages	Disadvantages	Refs
Maximum Value Compositing (MVC)	NDVI values are temporally or spatially aggregated. The highest NDVI value for the period and area considered is retained	Easy; no modelling; often works well because most errors are negative (Box 2)	Temporal aggregates might still be contaminated by cloud cover; the procedure will be biased by a single false high	[71]
Curve-fitting	Polynomial or Fourier functions are fitted to NDVI time-series	Easy; the trajectory can be predicted and the time-series can be summarized by several indices linked to the function	Medium-order polynomials can be too inflexible to recreate an entire seasonal NDVI pattern, and can smooth the data too much; Fourier analysis fails to characterize each annual NDVI trajectory separately; it can generate spurious oscillations in the NDVI time-series [72]; neither approach accommodates the skewed error structure (Box 2), and are therefore heavily affected by false lows or high	[72–74]
Step-wise logistic regression	A series of piecewise logistic functions are used to represent intra-annual vegetation dynamics. Four key transition dates are estimated: green-up, maturity (the date at which plant green leaf area is maximal), senescence and dormancy	Because the method treats each pixel individually without setting thresholds or empirical constants, it is globally applicable; it enables vegetation types to exhibit multiple modes of growth and senescence within a single annual cycle	Does not accommodate the skewed error structure (Box 2), and will therefore be heavily affected by false lows or high	[75]
Best Index Slope Extraction method (BISE)	NDVI observations are judged as trustworthy or not depending on whether the rate-of-change in the NVDI is plausible	The algorithm is robust to false highs that cause implausibly rapid increases in the NDVI (>0.1 in the NDVI value per day)	The sensitive point of this method is to estimate correctly to what extent a rate-of-change in the NVDI is plausible, according to the temporal resolution under consideration [72]	[63]
Weighted least-squares linear regression	A sliding-window combination of piecewise linear approximations to the NDVI time-series, putting more weight on 'local peaks' (NDVI values higher than the preceding and following observations). Tuning parameters are the weights affected to the local peaks and window widths	Works well when successive false lows are rare, so that local valleys occur separately, such as in the biweekly MVCs	When several false lows occur in sequence, they result in false local peaks, which bias the estimated value downwards. Thus, this approach might not be suitable for daily data, and its applicability will depend on the frequency of cloud contamination and the strength of seasonality	[76,77]

or spatial scales. For example, it is possible to get up to 365 NDVI pictures a year, whereas some animal responses can be gathered only once a year. However, depending on the biological question asked (e.g. the impact of a delayed or early start or end of the growing season, or vegetation availability in summer, on the performance of an animal population), only part of the information might be of relevance.

After smoothing (Figure 1; Table 1), the properties of the NDVI time-series can be summarized in a variety of related indices [21] (Figure 1; Table 2). Measures of overall productivity and biomass, such as the Integrated NDVI (INDVI) or the annual maximum NDVI value, measures of variability in productivity (e.g. the relative annual range of the NVDI) and a variety of phenological measures can be derived from NDVI time-series. Examples of measures include the rate of increase and decrease of the NVDI; the dates of the beginning, end and peak(s) of the growing season; the length of the growing season; the timing of the annual maximum NDVI; and the NDVI value at a fixed date, which might be relevant for animals that accumulate few reserves and are sensitive to the start of vegetation growth for their own reproductive success or for migrant animals matching the start of their migration with the resource dynamics.

Examples of successful applications of these measures include the correlation between the NVDI on the 1st of May and the body mass of reindeer calves in autumn in

Box 2. Noise in NDVI data

There are many complications, limitations and causes of error associated with satellite data, including sensor resolution and calibration [62], digital quantization errors [63], ground and atmospheric conditions [64], and orbital and sensor degradation [65]. NDVI data sets are generally well-documented, quality-controlled data sources that have been pre-processed to reduce many of these problems [57,58,60,61].

However, some noise is still present in the downloadable data sets and, therefore, NDVI time-series need to be smoothed before being used (Table 1, main text). Such noise is mainly due to remnant cloud cover, water, snow, or shadow, sources of errors that tend to decrease the NDVI values. False highs, although much less frequent [63], can also occur at high solar or scan angles (in which case the numerator and denominator in the NDVI ratio are both near zero) or because of transmission errors, such as line drop-out [63]. To minimize the problem of false highs, the downloadable products are generally based on low-angle observations wherever possible.

Most errors thus tend to decrease NDVI values. This unusual error structure, with high NDVI values being more trustworthy than low ones, breaks the assumptions of many standard statistical approaches. Further complications can arise because the error structure can vary in time and space. The most common approaches to smoothing NDVI time-series are presented in Table 1 (main text). For many purposes, the choice of smoothing method might not be crucial. For example, in a recent ecological study, similar estimates of spring phenology were obtained using either locally weighted regressions or a simple cumulative maximum throughout the season [51].

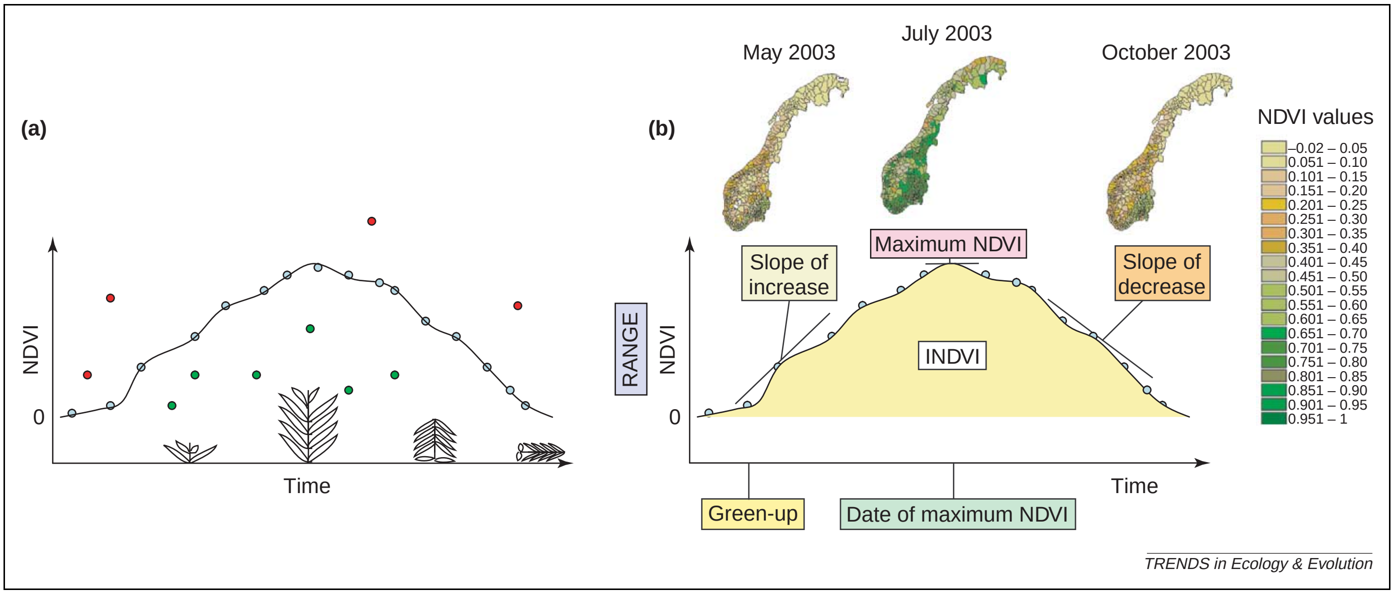

Figure 1. NDVI time-series. **(a)** Presentation of the three types of NDVI data that can be collected: data collected during a cloudy day (green circles), a clear day (blue circles), and 'false high' NDVI values (red circles) owing to transmissions errors. Because of this diversity in the quality of information contained in NDVI values, the time-series needs to be smoothed (Table 1). A typical smoother (black line) will rebuild the NDVI profile based mainly on clear-day estimates. The NDVI time-series over a year typically shows an increase that corresponds with the start of vegetation growth, the NDVI then peaks, establishing a plateau (which corresponds to a period of high photosynthetic activity), and then finally decreases, corresponding with the start of vegetation senescence. **(b)** Presentation of the different indices (the slopes of increase (spring) and decrease (fall), the maximum NDVI value, the Integrated NDVI (INDVI, i.e. the sum of NDVI values over a year), the date when the maximum NDVI value occurs, the range of annual NDVI values, and the date of Green-up (i.e. the beginning of the growing season)) that could be derived from NDVI time series over a year. Moreover, maps presenting NDVI values (ranging from 0 to 1) for Norway in May, July and October 2003 are also shown. Those data have been provided by the GIMMS group (http://ltpwww.gsfc.nasa.gov/gimms/htdocs/; the pixel size being 64 km^2).

Norway [48], with a delayed spring affecting directly and negatively the condition of the calf before entering winter. In North America, parturient female caribou selected annual calving grounds with greater areas of high rates of greening [24]. In Kenya, higher yearly average NDVI was correlated with lower species richness of mammals and plants, whereas standard deviation and coefficient of variation was correlated positively with species richness [52]. In North America, INDVI was reported to correlate positively with avian species richness [40], and the

Table 2. Pertinent measures for ecological studies that can be assessed from NDVI time-series

Index	Type of measure	Definition	Biological meaning	Comments	Refs
INDVI	Overall productivity and biomass	Sum of positive NDVI values over a given period	Annual production of vegetation	Not relevant when resource quality is at least as important as quantity (e.g. highly selective foragers)	[27,40]
Annual Maximum NDVI	Overall productivity and biomass	Maximum value of the NVDI over a year	Annual production of vegetation	Sensitive to false highs and noise correction	[78]
Relative annual range of the NVDI	Interannual variability in productivity	(Maximum NDVI value-Minimum NDVI value)/INDVI	Enables interannual comparisons of vegetation biomass	Sensitivity of the range definition to outliers in both directions	[79]
Rate of increase/ decrease of the NVDI	Phenological measure	Slope between two NDVI values at two defined dates, slopes of the fitted logistic curves to the NDVI time-series	Fastness of the greening up (spring) or the senescence (fall) phases	Sensitive to false highs and noises correction	[78]
Dates of the beginning or end of the growing season	Phenological measure	Dates estimated from threshold models or moving average procedures	Start of the green-up	Accuracy is linked to the temporal scale of the time-series considered (with the problem that higher temporal resolution leads to more contaminated data)	[21]
Length of the 'green' season	Phenological measure	Number of days where NDVI > 0; number of days between the estimated date of green-up and end of the growing season	In seasonal environments, number of days when food is available	Sensitive to false highs and noises correction	[80]
Timing of the annual maximum NDVI	Phenological measure	Date when the maximum NDVI value occurs within a year	Timing of the maximum availability of vegetation	Sensitive to false highs and noise correction	[29,79]

Box 3. Pitfalls and caveats

Although NDVI data sets are quality-controlled products, there are still pitfalls to avoid when using them.

Mixed pixels

A mixed pixel is defined as a pixel that encompasses water and land. The problem arises from the fact that water lowers the NDVI value recorded from the vegetation in mixed pixels. The lower NDVI values from mixed pixels have been previously documented [66], and in larger scale work (i.e. when the pixel size is much smaller than the area considered), excluding coastal pixels from the analysis might be a simple solution to problems associated with mixed pixels. In small-scale work, reducing the pixel size might also be an option.

Misregistration

Misregistration occurs when a NDVI value is wrongly assigned to a point on the globe as a result of errors in back-calculating the position of the satellite at the time the image was taken. Most misregistration errors are timing errors resulting from the onboard satellite clock. The ground speed of satellites is 7 km^{-1}, so timing errors of >1 s are of most concern [57,60]. The accuracy of the downloaded data should thus be checked by superimposing NDVI data on known maps.

Comparing NDVI values between pixels

Many factors affect NDVI variations within a pixel: plant architectural arrangement, interactions with canopy cover, height, composition of species, vegetation vigour, leaf properties and vegetation stress are some factors that can significantly affect the remotely sensed information [67,68]. Topography and altitude will also affect NDVI measurements [69]. Given that the same NDVI value might represent different conditions for different vegetation communities, comparing INDVI between close pixels is not advised without some previous knowledge of the area of interest.

Quality of the information in respect to spatial location

Additional caution should be taken when using the NVDI in specific spatial locations. For example, in the humid tropics, NDVI time-series, even when performed on a monthly basis, are highly contaminated by remnant cloud-cover effects [32]. Problems also occur at high latitudes and during the winter, because reflectance resolution deteriorates in such areas [70]. Moreover, during the winter, a greater incidence of spuriously high NDVI values is reported at higher latitudes ($>60°$ [66]) resulting from taking the ratio of very small reflectances. Finally, major errors also occur near the Equator (from 30°N to 30°S), owing to solar zenith angle variations within most of the satellite records. These errors are most pronounced for the satellite NOAA-11 over the period 1993–1994 [58]. Those particular noises, attached to specific spatial locations, should be taken into consideration while applying the chosen method to smooth the NDVI time series.

maximum NDVI value over a year correlated with the species richness of birds and butterflies [53]. In Spain, the minimum NDVI value over a year was demonstrated to correlate positively with the distribution of ticks [54].

All the studies reviewed here have coupled yearly measures based on the NDVI time-series to yearly measures based on data on animal populations. It is also possible to couple vegetation and animal data dynamics if the animal data are collected at a temporal resolution that matches the temporal resolution of the NDVI time-series considered. This dynamical approach has potential for future ecological studies.

Other vegetation indices

The NVDI is a vegetation index that has demonstrated its usefulness in many ecological studies. However, in some situations, other vegetation indexes might be more appropriate.

The relationship between the NVDI and vegetation can be biased in sparsely vegetated areas (e.g. arid to semi-arid zones in Australia) and dense canopies (e.g. Amazonian Forest [55]). In sparsely vegetated areas with a leaf area index (LAI) of <3, the NVDI is influenced mainly by soil reflectance, whereas for LAI>6 (i.e. in densely vegetated areas), the relationship between the NVDI and NIR saturates [9]. Therefore, in sparsely vegetated areas, the soil-adjusted vegetation index (SAVI; [55]) is recommended instead of the NVDI (e.g. [50]). However, the SAVI requires local calibration because it is difficult to predict how soil effects are manifested within large pixel areas, which aggregate soils and vegetation of many different types, each of which requires, in principle, separate calibration.

Another index that has appeared with MODIS is the Enhanced Vegetation Index (EVI; [56]). This index provides complementary information about the spatial and temporal variations of vegetation, while minimizing many of the contamination problems present in the NDVI, such as those associated with canopy background and residual aerosol influences. Whereas the NDVI is chlorophyll sensitive and responds mostly to RED variations, the EVI is more NIR sensitive and responsive to canopy structural variations, including LAI, canopy type and architecture. This index is thus meant to take full advantage of the new state-of-the-art measurement capabilities of MODIS. Additionally, EVI does not become saturated as easily as the NDVI when viewing rainforests and other areas of the Earth with large amounts of green material. However, EVI has been developed on MODIS data and so data are only available from 2000 onwards.

Conclusions and perspectives

The NVDI has already been successfully applied to research on temporal and spatial trends and variation in vegetation distribution, productivity and dynamics, to monitor habitat degradation and fragmentation, and the ecological effects of climatic disasters such as drought or fire. The encouraging results reviewed here suggest that NDVI will become an extremely useful tool for terrestrial ecologists aiming to gain a better understanding of how vegetation dynamics and distribution affect diversity, life-history traits, movement patterns and population dynamics of animal populations. The global coverage of the NDVI suggests that it could be used to predict the ecological effects of environmental change on ecosystems functioning and animal population dynamics and distributions, enabling researchers to better understand the impact of humans on the environment.

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