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.

Recent ecological studies have highlighted the relevance of the Normalized 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 $\text{NDVI} = (\text{NIR} - \text{RED})/(\text{NIR} + \text{RED})$, 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.
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, multiple 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 $EVI = \frac{G*(NIR - RED)}{(NIR + c1*RED) - c2*BLUE + L}$, 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 needle 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 $\frac{(NIR - RED)}{(NIR + RED + L)}*(1 + L)$, 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 la 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], CO₂ 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 biomes ([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 NDVI 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 NDVI 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 contemporary 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 NDVI was used to explain a significant amount of variation (from 10 to 20%) in the date of the first (the NDVI in autumn) and last (the NDVI in spring) frost, as well as the length of the frost-free period (the NDVI in autumn) [39].

**Using the NDVI to assess trophic interactions**

So far, the NDVI has been used predominantly in studies focusing on the effects of environmental change on plants.
were all found to be later in Norway than in France[51]. and the rutting and calving of red deer spring vegetation flush, identified from NDVI time-series, with the NVDI in spring[24,48], whereas the timing of the Rangifer tarandus breaks [50]. Body mass and calf survival of reindeer understanding of the spatial distribution of locust out- lations [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 NDVI 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].

However, the NDVI could also be used to gain novel insight into trophic inter-linkages. The use of the NDVI 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 NDVI, 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].

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.

### Table I. The different NDVI data sets

<table>
<thead>
<tr>
<th>Data set</th>
<th>Satellite</th>
<th>Instrument</th>
<th>Temporal span</th>
<th>Temporal resolution</th>
<th>Missing data</th>
<th>Range</th>
<th>Website</th>
</tr>
</thead>
<tbody>
<tr>
<td>GVI</td>
<td>NOAA</td>
<td>AVHRR</td>
<td>May 1982–Present</td>
<td>Week, monthly, seasonal</td>
<td>January 1995–16 km</td>
<td><a href="http://www2.ncdc.noaa.gov/docs/gviiug/index.htm">http://www2.ncdc.noaa.gov/docs/gviiug/index.htm</a></td>
<td></td>
</tr>
<tr>
<td>GIMMS</td>
<td>NOAA</td>
<td>AVHRR</td>
<td>July 1981–Present</td>
<td>Bimonthly index (10-day for Africa)</td>
<td>None–8 km</td>
<td><a href="http://ftpwww.gsfc.nasa.gov/gimms/htdocs/">http://ftpwww.gsfc.nasa.gov/gimms/htdocs/</a></td>
<td></td>
</tr>
<tr>
<td>MOD13</td>
<td>TERRA</td>
<td>MODIS</td>
<td>February 2000–Present</td>
<td>16 days</td>
<td>None–250 m–1 km</td>
<td><a href="http://modis.gsfc.nasa.gov/">http://modis.gsfc.nasa.gov/</a></td>
<td></td>
</tr>
<tr>
<td>VGT</td>
<td>SPOT</td>
<td></td>
<td>April 1998–Present</td>
<td>10 days</td>
<td>None–1 km</td>
<td><a href="http://www.spotimage.fr">http://www.spotimage.fr</a></td>
<td></td>
</tr>
</tbody>
</table>

For the pied flycatcher Ficedula hypoleuca, the NDVI 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

<table>
<thead>
<tr>
<th>Procedure</th>
<th>What it does</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Refs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Value</td>
<td>NDVI values are temporally or spatially aggregated. The highest NDVI value for the period and area considered is retained</td>
<td>Easy; no modelling; often works well because most errors are negative (Box 2)</td>
<td>Temporal aggregates might still be contaminated by cloud cover; the procedure will be biased by a single false high</td>
<td>[71]</td>
</tr>
<tr>
<td>Compositing (MVC)</td>
<td>Polynomial or Fourier functions are fitted to NDVI time-series</td>
<td>Easy; the trajectory can be predicted and the time-series can be summarized by several indices linked to the function</td>
<td>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</td>
<td>[72–74]</td>
</tr>
<tr>
<td>Curve-fitting</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Step-wise logistic regression</td>
<td>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</td>
<td>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</td>
<td>The sensitive point of this method is to estimate correctly to what extent a rate-of-change in the NDVI is plausible, according to the temporal resolution under consideration [72]</td>
<td>[63]</td>
</tr>
<tr>
<td>Best Index Slope Extraction method (BISE)</td>
<td>NDVI observations are judged as trustworthy or not depending on whether the rate-of-change in the NDVI is plausible</td>
<td>The algorithm is robust to false highs that cause implausibly rapid increases in the NDVI (&gt; 0.1 in the NDVI value per day)</td>
<td>The sensitive point of this method is to estimate correctly to what extent a rate-of-change in the NDVI is plausible, according to the temporal resolution under consideration [72]</td>
<td></td>
</tr>
<tr>
<td>Weighted least-squares linear regression</td>
<td>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</td>
<td>Works well when successive false lows are rare, so that local valleys occur separately, such as in the biweekly MVCs</td>
<td>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</td>
<td>[76,77]</td>
</tr>
</tbody>
</table>

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 NDVI) 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 NDVI; 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 NDVI on the 1st of May and the body mass of reindeer calves in autumn in...
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

<table>
<thead>
<tr>
<th>Index</th>
<th>Type of measure</th>
<th>Definition</th>
<th>Biological meaning</th>
<th>Comments</th>
<th>Refs</th>
</tr>
</thead>
<tbody>
<tr>
<td>INDVI</td>
<td>Overall productivity and biomass</td>
<td>Sum of positive NDVI values over a given period</td>
<td>Annual production of vegetation</td>
<td>Not relevant when resource quality is at least as important as quantity (e.g. highly selective foragers)</td>
<td>[27,40]</td>
</tr>
<tr>
<td>Annual Maximum NDVI</td>
<td>Overall productivity and biomass</td>
<td>Maximum value of the NDVI over a year (Maximum NDVI value-Minimum NDVI value)/INDVI</td>
<td>Annual production of vegetation</td>
<td>Sensitive to false highs and noise correction</td>
<td>[78]</td>
</tr>
<tr>
<td>Relative annual range of NDVI</td>
<td>in productivity</td>
<td>Interannual variability</td>
<td>Enables interannual comparisons of vegetation biomass</td>
<td>Sensitivity of the range definition to outliers in both directions</td>
<td>[79]</td>
</tr>
<tr>
<td>Rate of increase/decrease of NDVI</td>
<td>Phenological measure</td>
<td>Slope between two NDVI values at two defined dates, slopes of the fitted logistic curves to the NDVI time-series</td>
<td>Fastness of the greening up (spring) or the senescence (fall) phases</td>
<td>Sensitive to false highs and noise correction</td>
<td>[78]</td>
</tr>
<tr>
<td>Dates of the beginning or end of the growing season</td>
<td>Phenological measure</td>
<td>Dates estimated from threshold models or moving average procedures</td>
<td>Start of the green-up</td>
<td>Accuracy is linked to the temporal scale of the time-series considered (with the problem that higher temporal resolution leads to more contaminated data)</td>
<td>[21]</td>
</tr>
<tr>
<td>Length of the ‘green’ season</td>
<td>Phenological measure</td>
<td>Number of days where NDVI &gt; 0; number of days between the estimated date of green-up and end of the growing season</td>
<td>In seasonal environments, number of days when food is available</td>
<td>Sensitive to false highs and noise correction</td>
<td>[80]</td>
</tr>
<tr>
<td>Timing of the annual maximum NDVI</td>
<td>Phenological measure</td>
<td>Date when the maximum NDVI value occurs within a year</td>
<td>Timing of the maximum availability of vegetation</td>
<td>Sensitive to false highs and noise correction</td>
<td>[29,79]</td>
</tr>
</tbody>
</table>
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 [68], 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 $7 \text{ km s}^{-1}$, so timing errors of $\sim 1 \text{s}$ 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 NDVI 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 ($\geq 60^\circ$ [86]) resulting from taking the ratio of very small reflectances. Finally, major errors also occur near the Equator (from $30^\circ \text{N}$ to $30^\circ \text{S}$), 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 NDVI (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.

Acknowledgements
We thank the Distributed Active Archive Center (Code 902.2) at the Goddard Space Flight Center, Greenbelt, MD, 20771, for producing the data in their present form and distributing them. The original data products were produced under the NOAA/NASA Pathfinder program, by a processing team headed by Mary James of the Goddard Global Change Data Center; and the science algorithms were established by the AVHRR Land Science Working Group, chaired by John Townshend of the University of Maryland. Goddard’s contributions to these activities were
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