NDVI as indicator of degradation

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A method to interpret remote sensing images is applied to observe change in forest health over time.

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Forest degradation has become a serious problem, especially in developing countries. In 2000, the total area of degraded forest in 77 countries was estimated at 800 million hectares (ha), 500 million ha of which had changed from primary to secondary vegetation (ITTO, 2002). Among other impacts, the process of forest degradation represents a significant proportion of greenhouse gas emissions. There is an urgent need to measure and analyse it, in order to design action to reverse the process.

This article describes how one method of analysing remote sensing data in conjunction with field data to monitor forest degradation was put into practice. It presents a study carried out to identify relationships between indicators of forest functions and the normalized difference vegetation index (NDVI), which is estimated through analysis of satellite images to give an indication of "greenness". The premise is that NDVI is an indicator of vegetation health, because degradation of ecosystem vegetation, or a decrease in green, would be reflected in a decrease in NDVI value. Therefore, if a relationship between the quantity of an indicator – aerial biomass – in various forest ecosystems and the NDVI can be identified, processes of degradation can be monitored.

Natural vegetation, Mexico

FAO/C. PALMBERG-LERCHE

MEASURING CHANGE

Remote sensing and phenology

One of the most important applications of remote sensing is the monitoring of processes occurring on Earth.

Images can be used for the analysis of short-term processes, for example monitoring the growth cycle of crops to evaluate the yields of one harvest. Satellite images taken at various stages in the cropping cycle for a single year are evaluated, including: soil preparation, sowing, establishment of seedlings, active growth, flowering, fruiting and translocation of nutrients or ripening of fruit and harvesting.

They can also be for the analysis of medium- or long-term processes. Analyses of forest degradation and change in land use are major examples of applications of this approach. Images from different years can be compared. These images must be captured during the same time of year so as to minimize the expression of variations in such factors as light quality, the geometry of the observation and differences in the behaviour of a community over the course of the year, in the case of plant ecosystems (Singh, 1986; Mouat *et al*., cited by Chuvieco, 1998).

Both are *phenological* approaches. Phenology involves studying the timing of life cycle events of plants and animals, and in particular, in relation to changes in season and climate. In the case of annual crops, observing change in images is relatively easy. Changes in reflectance of light over the course of crop growth are evident and occur over short periods of time. In the case of forest ecosystems, the natural processes, and the approaches to observing them, are protracted. Behaviour in an individual takes place over a longer period (5 to 25 years), which also applies to forest plantations that are "pure ecosystems" (i.e. same-age stands). Over this period of time, the phases of planting, establishment of seedlings and active growth up to the time of commercial maturity can be distinguished, encompassing the more complex dynamics of flowering, fruiting, change of leaves and branches, and thickening of the trunk, in a constant process of change in the above-ground living matter, or aerial biomass.

Observation of phenological processes is more complicated in a primary or natural stand containing individuals of different ages and species, in which each exemplar has its own rhythm or phenological behaviour: flowering, fruiting, loss of leaves and regrowth, and survival strategy in terms of competition for light, nutrients and water.

NDVI and phenology

There are various methodologies for studying seasonal changes in vegetation through satellite images, one method of which is to apply vegetation indices relating to the quantity of greenness (Chuvieco, 1998). The NDVI is a measurement of the balance between energy received and energy emitted by objects on Earth. When applied to plant communities, this index establishes a value for how green the area is, that is, the quantity of vegetation present in a given area and its state of health or vigour of growth. The NDVI is a dimensionless index, so its values range from –1 to +1.

In a practical sense, the values that are below 0.1 correspond to bodies of water and bare ground, while higher values are indicators of high photosynthetic activity linked to scrub land, temperate forest, rain forest and agricultural activity.

THE STUDY

Background, data sets

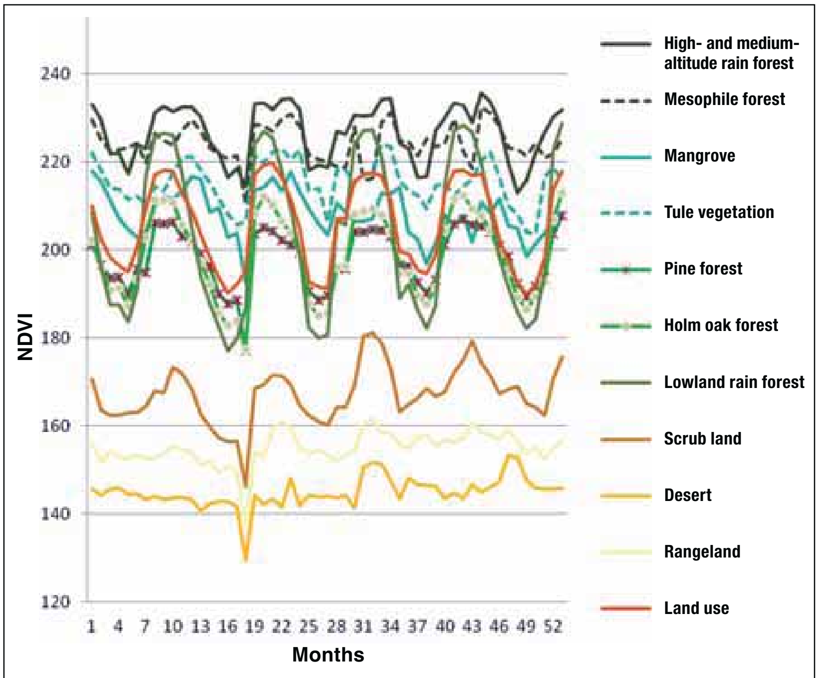
Drawing on remote sensing imagery and field surveys, the study sought to establish a relationship between NDVI and aerial biomass. First, images had to be collected. Then NDVI values had to be established through analysis of the imagery. Then, these values had to be applied to different vegetation communities both to validate the method and to establish a baseline for observations. They were then observed over time. Finally, NDVI could be correlated to aerial biomass, an indicator of forest health, through field-survey data, in order to establish the validity of the method and to make it applicable to monitoring forest use.

The study focused on Mexico, which has a land area of almost two million km^2. Given its particular location and relief, the country features a diversity of

TABLE 1. Classification of field observations between 2004 and 2007 used for NDVI analysis

Vegetation community	National Statistics and Geography Institute key	Number of sites
Holm oak forest	Holm oak and holm oak-pine	20 139
Pine forest	Pine, fir, juniper, cypress, juniper and pine-holm oak with predominance of pine	6 276
Desert and dune	Microphyllous desert scrub land	199
Mangrove	*Rhizophora* spp.	980
Scrub land	Various types of scrub land	10 945
Mesophile forest	Very moist montane forest	1 526
Rangeland	Natural rangeland and through presence of sodium and chalk	235
High- and medium-altitude rain forest	High- and medium-altitude rain forest (deciduous or evergreen)	16 976
Lowland rain forest	Lowland rain forest (deciduous or evergreen)	6 470
Tule vegetation	*Thyphus* spp.	190
Without plant cover	Without plant cover	1 229

1
Average NDVI, by month, for established classes of vegetation



Note: NDVI is translated and mathematically scaled to a range of 0 to 256.

ecosystems and life zones, ranging from tropical to temperate. Data for the study included satellite images and information obtained from inventories. The satellite images were obtained from MODIS, the Moderate Resolution Imaging Spectroradiometer, launched by the United States National Aeronautics and Space Administration on board two satellites, which is designed to provide measurements in large-scale global dynamics.

The National Forest and Soil Inventory (INFyS) of Mexico, maintained by the National Forest Commission (CONAFOR), provided basic information and ground truth for the estimates. INFyS data were collected during the period 2004–2007 and updated in 2008–2009.

Establishing NDVI values

In order to estimate the phenological behaviour of wooded ecosystems, composites of images from MODIS for cloudless months, with a spatial resolution of 500 m, were analysed. These images were processed by the Maryland Institute for Advanced Computer Studies (United States of America). Fifty-three consecutive composite images of 30 days from 16 November 2000 to 13 August 2005 were used. NDVI values were calculated for the images.

Then the NDVI values had to be correlated to vegetation types present at the various sites. Field data were obtained from INFyS in a systematic stratified sampling covering all of the country's ecosystems. The vegetation community type assigned to an area indicated the vegetation most frequently observed in the field for each of the sampled sites. Labels used for this exercise were based on the classification system of the Land Use and Vegetation Map of the National Statistics and Geography Institute used in its Series II (INEGI, 2000). A total of 65 165 sites were observed and classified as seen in Table 1.

The sampled sites were superimposed on the series of 53 images that had been developed from the monthly composites of MODIS images. An average NDVI value was calculated for each type of plant community for each month in order to assess its behaviour over the course of the year.

Observations

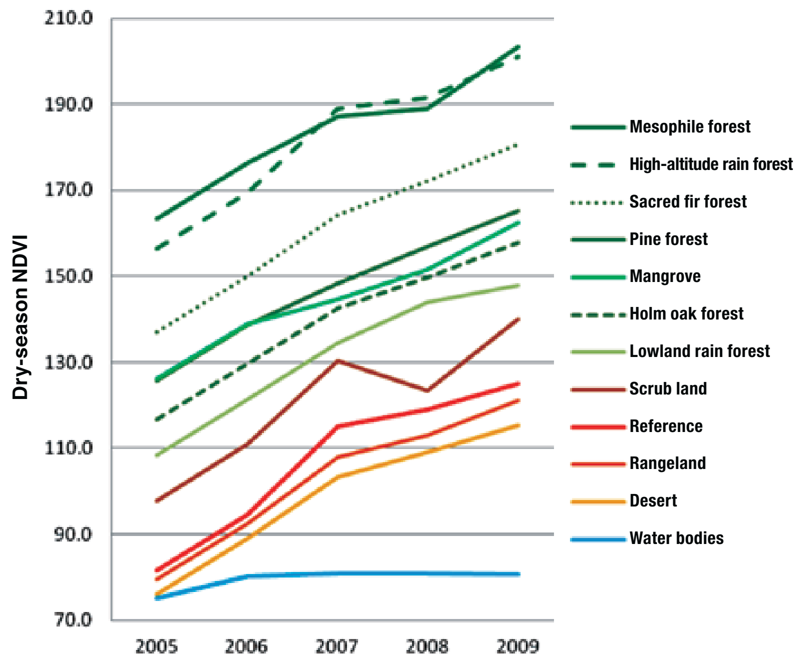
The highest NDVI values correspond to high- and medium-altitude rain forests and mesophile montane forests, which remained above the reference threshold for the quantity of greenness throughout the year (Figure 1). This threshold has a value of approximately 190 (see note, Figure 1, regarding NDVI values) and can be linked to the evergreen habit of the ecosystem or can be used to separate forests from other wooded land.

A sinusoidal trend or annual cyclical behaviour is a classic response to a regular cycle of rainfall and storage of water in the ground. The minimum NDVI values occur between February and April each year, corresponding to the driest period. The maximum NDVI values occur during July and August, which are the months with the highest rainfall. There is further variation, as the dates of the rainy season vary depending on latitude. Mexico stretches over a considerable distance from north to south.

The extreme oscillations show that lowland rain forests have the greatest range in their cycle. As with holm oak forests and pine forests, they have values below the reference threshold value of 190 between February and May in the years analysed. Dips in the NDVI value occur because the level of greenness reflected in these periods is low, as a result of falling leaves or change in their colour.

Readers should be aware that the value shown is the combined response of the whole ecosystem (soil and grassy, shrub and tree layers). Therefore, it is also possible that, during this period, part of the

2
Annual behaviour of the dry-season NDVI for various types of ecosystem



Note: NDVI is translated and mathematically scaled to a range of 0 to 256.

grassy layer dries out completely in these forests because of seasonal water stress.

The vegetation communities with the lowest NDVI values are deserts, where leaves are very sparse, followed by rangeland and scrub land. These communities show no sinusoidal trend; rather, their response is that of a region that has irregular rainfall. Analysis of degradation processes in these communities is made more complicated by such fluctuation.

Mangrove and tule ecosystems present the most complex behaviour, in terms of NDVI values. While the values are always above the reference value, they follow no regular pattern, with no clearly defined peaks. Their value is very much affected by fluctuations in water level.

The sample included a series of sites classified as "land use", a term that, for the most part, corresponds to the presence of agriculture. These areas show a sinusoidal behaviour that is slightly narrower than that of lowland rain forest. Average NDVI values of these areas never fall below the reference threshold. These consistently "green" values are difficult to explain, if mechanized annual crops are involved; one would have expected the values during the period of preparation of the soil to be close to those of bare ground. The phenomenon can perhaps be attributed to the fact that crops are being grown without any type of mechanization.

The exercise reflects the fact that, when carrying out a multitemporal analysis of processes, an important consideration is the dates on which the satellite images are taken. It is vital to compare images corresponding to the same dates, as there are differences in the vigour of growth during the different months of the year, and pronounced differences between the dry and rainy seasons – even in evergreen stands.

This type of analysis can show the natural changes to vegetation over a period of time. For it to be applied to such purposes as monitoring forest degradation, it is necessary to separate the fluctuations in greenness resulting from the natural oscillation of vegetation from those caused by other processes.

NDVI from year to year

The next step was to establish annual behaviour of NDVI for the different vegetation areas. The dry season was selected because there is less cloud cover affecting the MODIS images and because arable land is generally bare, and is, therefore, distinguishable, during this period.

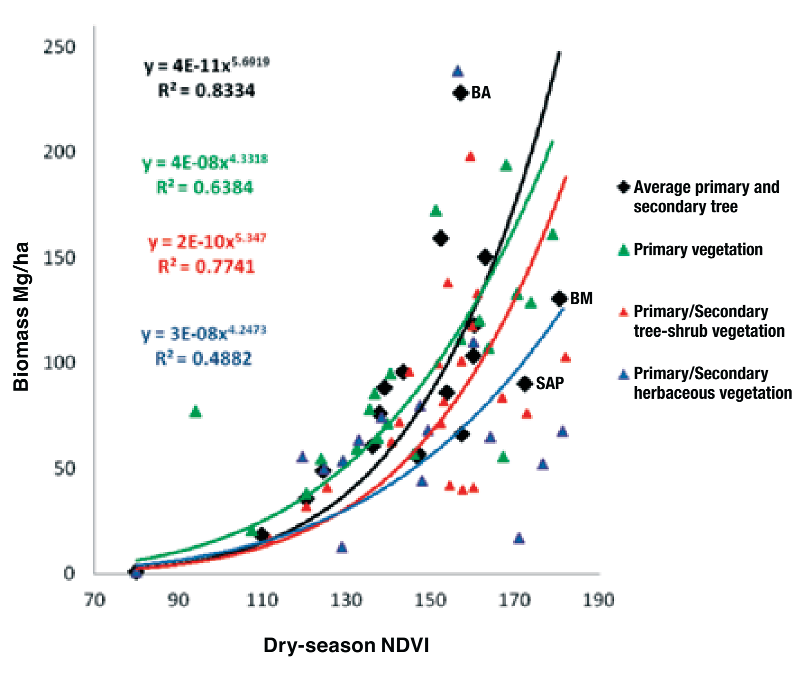
A composite of MODIS images was prepared with a spatial resolution of 250 m, using images obtained between 15 February and 15 April each year, the dry season. Average NDVI values were calculated for the period. The points observed in the previous round were superimposed, and the average behaviour was calculated for each type of plant community (Figure 2).

A definite pattern is seen relating to the biomass contents of the various ecosystems. Among the various vegetation types, an almost constant increase in NDVI is seen over the period. Exceptions are seen in mesophile montane forest, high- and medium-altitude rain forest and scrub land, which show almost no fluctuation between the 2007 and 2008 seasons.

Linkages to aerial biomass

Aerial biomass was chosen as the variable indicator of forest function to compare with the behaviour of the NDVI. A forest can experience a change in cover without necessarily a loss from its original condition, but a negative change to a structure that can diminish its capacity to provide services and products can be considered a form of degradation.

Twenty-five thousand points were measured in the field for the inventory. Each measurement point, or plot,



Note: NDVI is translated and mathematically scaled to a range of 0 to 256.

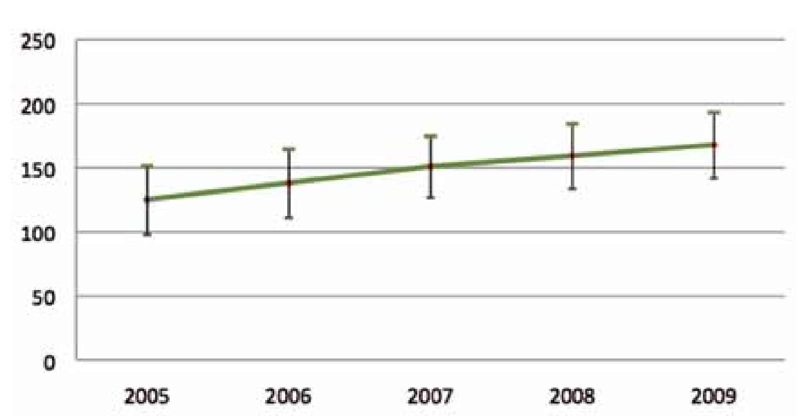
3
Comparison between dry-season NDVI and the quantity of aerial biomass per type of plant community

comprised four sites, or subplots. In each site, measurements of variables were taken for all trees with a diameter at breast height (DBH) of more than 7.5 cm. These variables included number of trees, number of species, number of live trees, number of stumps, total tree height, commercial height, clean height, DBH, diameter of the crown and basal areas, together with 21 other quantitative variables and some 45 qualitative variables connected to, for example, regrowth, impact condition, state of the topsoil and humus, and use of the resource (CONAFOR, 2011).

The quantity of aerial biomass in tonnes per ha was estimated for 16 842 plots measured in the field for INFyS (ECOSUR, 2009). Biomass equations were established for each ecosystem based on a review of the literature. Most equations were generated from materials that reflect a commercial perspective, and pertain to conifer and broadleaved ecosystems in temperate regions.

Allometric equations were developed for 120 of the almost 3 000 species listed in INFyS. Most of the models use DBH and height as independent variables. Information from the measurement of regrowth was not used to estimate biomass, arid-zone succulent species were omitted, and no equations estimating biomass or timber volume were drawn up for certain communities (thalias, savannahs, tule, palms, mangroves and some rain forests). Of the 1 305 307 trees observed, 1 230 127 individuals were taken into consideration (see Figure 4; ECOSUR, 2009). The 16 842 plots were superimposed on the NDVI images and were classified according to both type of plant community and condition (primary, primary with secondary tree vegetation and primary with secondary shrub vegetation) (Figure 3).

The relationship between aerial biomass and NDVI shows an exponential behaviour in which the origin is the NDVI value of bodies of water, for which an aerial biomass of 0 is assumed. The highest biomass values correspond to fir forest (BA), while the highest NDVI values correspond to mesophile montane forest (BM), followed by evergreen high-altitude rain forest (SAP). In estimating the aerial biomass of the latter two communities, general equations suggested by the Intergovernmental Panel on Climate Change Good Practice Guidance for Land Use, Land-Use Change and Forestry are used (IPCC, 2003). The overall relationship shows a correlation coefficient (R^2) of 0.8334.



4
General behaviour of NDVI, 2005–2009, across sample re-measured in 2009

It should be noted that the shapes that compose rain forests and mesophile montane forests are very different from those of conifers, and they are, therefore, underestimated in the model. On the other hand, there is also "overestimation", in that only trees with a DBH of more than 7.5 cm are considered in estimating biomass, while the satellite-measured NDVI encompasses the whole response of the ecosystem (tree, shrub and grassy layers).

Figure 3 shows a decline in the relationship between aerial biomass and NDVI, depending on condition or successive state. This trend indicates that in a given community there is more aerial biomass for primary ecosystems than for those affected by disturbance.

FOLLOW-UP

An initiative has been launched to remeasure the sites visited in the first round. Sites were revisited in 2009 and will be visited again in 2012. Thus, information is, and will continue to be, available on growth and changes in forest functions in 20 percent of the 25 000 established plots. Information on soil, fires and health can be estimated (INFyS database query, 2010).

In the first re-measurement, NDVI values of the 2009 INFyS field measurements were taken, and analysis was conducted for both points that had suffered some kind of disturbance and points that had not.

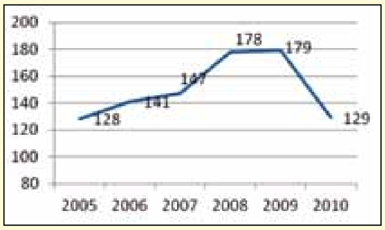
Of the total of 3 533 plots measured in 2009, 3 486 indicated an increase in NDVI over the initial measurement. The general behaviour of the NDVI is shown in Figure 4. Behaviour among specific classes of vegetation was also analysed.

The box, and its illustrative table, figure and photographs, presents the data of one point from the group – Plot 56890 – Campeche. This point was among those taken at random in order to demonstrate both the condition at the first and second field measurements and how the NDVI can vary. Further discussion (Figure 5) presents results for one grouping – land without plant cover. It should be taken into account that the field points measured evaluate only 1 600 m^2 and are representative of 1 ha, and that the whole area of the pixels is 6.25 ha.

Follow-up: Plot 56890 – Campeche

Plot 56890 presented an interesting case. Dry-season NDVI observed up to 15 April 2009 showed that the plot had recently been burned. NDVI behaviour for some years could be identified (Figure), but further analysis will have to be carried out.

In August 2005, the plot showed sub-evergreen medium-altitude rain forest, and 192 trees measured (Photo, left). The April 2009 observation shows no plant cover and 0 individuals (Photo, right; Table).



Behaviour of NDVI, 2005–2010, Plot 56890

Survey results, Plot 56890 – Campeche

Visit	No. trees	DBH *cm*	Crown diameter *m*	Cover *%*	Total height *m*	Stumps
09/08/2005	192	11.82	2.51	60.1	8.98	0
17/04/2009	0	0	0	0	0	0

5
Plots reported as "without vegetation cover" in 2009 survey, by case

Of the 3 533 plots measured in 2009, a reduction in the NDVI was detected in 47.

Plots reported as being without plant cover, from the 2009 sample, numbered 258 (Figure 5).

Among this group, four classes of case were identified:

- 129 plots were not visited in the first round because they were interpreted as "land use" and were validated by interpreting images; no reduction in NDVI was detected for any of these cases (green points, on map);
- 53 are plots that corresponded to "without plant cover" in 2004–2007 and were still without it in 2009; no reduction in NDVI was detected for any of these cases (yellow points, on map);
- 61 were incorrectly labelled in 2004–2007. Forest was indicated, but a revision of photographs and data indicated that the plots were, in fact, "without vegetation cover"; no reduction in NDVI was detected for any of these cases (red points, on map);
- For 14 plots, the 2004–2007 observation showed plant cover corresponding to some type of forest, whereas the 2009 observation showed them as being without plant cover (blue points, on map).

CONCLUSIONS

There are limitations to use of the NDVI to measure forest degradation, and areas for improvement. As phenology plays an important role in the analysis of change processes, the dates of the MODIS images used to assess those processes must be selected carefully. When processing the images, care must be taken to eliminate clouds, shadows of clouds, shadows created by the topography and saturation values in the numbers generated by the geometry of the satellite observation or by the presence of water on the leaves of trees.

Regression models can be improved. One way is by comparing two temporal measurements of a single point of INFyS. Another is by taking into account such factors as regrowth. Other measured variables are also contained in INFyS, such as standing dead trees and stumps, that could also enable a better understanding of the dynamics of the forest at each point observed, as well as the age of the sample population, in coniferous communities. Most allometric equations for estimating aerial biomass are based only on the height of the individual and the DBH; aspects such as the canopy, the diameter of branches and the basal area are not taken into account. As estimates of biomass in mesophile montane forest and rain forest ecosystems are refined, the method will prove more representative of change.

Attention should be paid to such other aspects as climate anomalies that have a major impact on the vigour of growth. For example, "wet" years associated with the la Niña/el Niño phenomena will lead to an increase in the NDVI, while "dry" years generate very low values in the change indicator.

Despite limitations pertaining to the imaging, including the resolution of the images, and limitations in the estimation of aerial biomass, the regression model of 0.83 is very good. Images generated by the MODIS sensor are suitable for analysis of changes resulting from degradation, when the impact has been sufficiently great to generate a change in radiometry, and, thus, in the NDVI. The NDVI has an anticipated behaviour and can be used as an indicator. ◆

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