EFFECTS OF SPECTRAL, SPATIAL AND RADIOMETRIC CHARACTERISTICS ON REMOTE SENSING VEGETATION INDICES

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ABSTRACT

Vegetation indices derived from satellite image data have become one of the primary information sources for monitoring vegetation conditions and mapping land cover change. The most widely used vegetation index in this context is NDVI, the Normalized Difference Vegetation Index, which is a function of red and near-infrared spectral bands. Given that the spectral and spatial characteristics of imagery in the red and near-infrared vary from sensor to sensor, NDVI values based on data from different instruments will not be directly comparable. The present study demonstrates the impact of changes in spectral bandwidth and spatial scale on NDVI derived from Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) data acquired at 20-m resolution over a forested region in Southeastern British Columbia. For this purpose, the 10-nm AVIRIS data were spectrally and spatially aggregated in the red and near-infrared to simulate bandwidths from 10 nm to 150 nm for ground resolutions varying from 20 m to 1100 m. Sensor-specific spectral bands and spatial resolutions such as those for SPOT HRV, Landsat TM, NOAA AVHRR, EOS MODIS and Envisat MERIS were also generated. NDVI values were then calculated using atmospherically corrected surface reflectances for forestry-related targets for the entire simulated band set at the various scales. The results indicate that the NDVI is significantly affected by differences in spectral bandwidth, especially for the red band, and that changes in spatial resolution lead to less pervasive but more land cover specific effects on NDVI. Results also indicate that NDVI is not very sensitive to the location of the near-infrared spectral band, provided that the bandwidth is no wider than 50 nm and the atmospheric correction for water vapour absorption is adequate. If either proviso is relaxed, the wavelength placement of the near-infrared spectral band is more critical, the optimum location being in the 850 to 880 nm range. Finally, some results were also

generated for several other vegetation indices that make straightforward use of atmospherically corrected red and near-infrared spectral bands.

1. INTRODUCTION

Satellite image data have become an important source of information for monitoring vegetation and mapping land cover and land cover change on regional, continental, and global scales. Various vegetation indices have been developed for qualitative and quantitative assessment of vegetation using remote spectral measurements (Bannari et al., 1995). In particular, sensors with spectral bands in the red (RED) and near-infrared (NIR) lend themselves well to vegetation monitoring since the difference between the red and near-infrared bands has been shown to be a strong indicator of the amount of photosynthetically active green biomass (Tucker, 1979). As a result, widespread use is being made of the Normalized Difference Vegetation Index (NDVI), which is defined as (NIR - RED) / (NIR + RED). The importance of defining the units of the values in the RED and NIR spectral bands is discussed later in this paper.

The NDVI from remote sensing is increasingly being used as an indirect means of study for biophysical plant canopy properties (Pinty et al., 1993), including its relationship to biomass (Pearson and Miller, 1972; Tucker, 1979; Elvidge and Lyon, 1985), leaf area index (Holben et al., 1980; Badhwar et al., 1986; Clevers, 1988, 1989; Spanner et al., 1990; Baret and Guyot, 1991; Chen, 1996), agriculture and rangeland (Jackson et al., 1983; Huete and Jackson, 1987; Bullock, 1992; Malthus et al., 1993; McNairn and Protz, 1993; Thenkabail et al., 1994), primary productivity (Tucker and Sellers, 1986), photosynthetic radiation (Asrar et al., 1984; Choudhury, 1987; Baret and Guyot, 1991; Goward and Huemmerich, 1992; Chen, 1996), carbon dioxide (Tucker et al., 1986; Cihlar et al., 1992), meteorological parameters (Nicholson et al., 1990) and ecological parameters (Cihlar et al., 1991), among others. Perhaps the most prevalent use of NDVI is in multi-temporal mapping of vegetation dynamics based on maximum-NDVI compositing (Townshend et al., 1985; Holben, 1986; Gutman, 1989; Wiegand et al., 1991; Viovy et al., 1992; Loudjani et al., 1994), increasingly on continental or global scales (Townshend and Justice, 1986; Townshend et al., 1994; Smith, 1994).

NDVI values can vary significantly as a function of sensor calibration (Price, 1987; Goward et al., 1991), atmospheric conditions (Deering and Eck, 1987; Singh and Saull, 1988; Kaufman and Tanré, 1992; Myneni and Asrar, 1994), directional surface reflectance effects (Kirchner et al., 1981; Holben et al., 1986; Lee and Kaufman, 1986; Paltridge and Mitchell, 1990; Koslowsky, 1993), and terrain relief (Teillet and Staenz, 1992; Burgess and Lewis, 1994). Special attention has also been paid to soil background effects and soil indices (Richardson and Wiegand, 1977; Huete, 1988; Baret et al., 1989, Major et al., 1990; Huete and Tucker, 1991; Qi et al., 1994a, b; Huete et al., 1994). Alternative vegetation indices have been formulated or proposed to try to overcome some of these effects, but their discussion is beyond the realm of this paper. Aman et al. (1992) have examined the correspondence between spatial integration of NDVI as opposed to computing NDVI from spatially integrated reflectances.

Given that the characteristics of spectral bands in the red and near-infrared vary distinctly from sensor to sensor, NDVI values based on data from different instruments will not be directly comparable. The spatial resolution also varies significantly between sensors, as well as within a given scene in the case of wide-angle and oblique sensors. As a result, NDVI values will vary according to combinations of the heterogeneity and scale of terrestrial surfaces and pixel footprint sizes. Therefore, the question arises as to the impact of differences in spectral and spatial resolutions on vegetation indices like the NDVI. A related issue is the effect of the wavelength location of the near-infrared spectral band for which there are several options in the so-called near-infrared plateau region of the reflectance spectrum of vegetation. In order to address these questions, Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) data acquired over a forested region in Southeastern British Columbia were atmospherically corrected and used to generate NDVI values for a variety of spectral and spatial resolutions. The data set is well suited to this investigation since AVIRIS collects imagery at 20 m ground resolution in 224 spectral bands, each approximately 10 nm wide, in the 400 nm to 2450 nm region (Vane et al., 1993). Pixel averages for several forestry-related land cover types (conifers, mixed stands, clear-cuts, etc.) were extracted from the imagery for NDVI calculations. Results were also generated for several other vegetation indices that make straightforward use of atmospherically corrected red and near-infrared spectral bands. The intent is not to compare different vegetation indices but rather to illustrate the impacts of spectral, spatial, and radiometric characteristics on several vegetation indices of interest.

2. RADIOMETRIC PROCESSING CONSIDERATIONS

The discussion in this section focuses on NDVI as an example, but the same principles apply to any other vegetation index. Values of NDVI for a given vegetation target will not only differ because of the spectral and spatial characteristics of the sensor, but also as a function of the radiometric processing applied to the image data (Guyot and Gu, 1994). The properties of NDVI space will vary considerably depending on whether NDVI is defined in terms of digital signal levels, top-of-the-atmosphere radiances, top-of-the-atmosphere reflectances, or atmospherically-corrected surface reflectances. Roderick et al. (1996) have examined the radiometric precision (as opposed to accuracy) of the NDVI derived from NOAA Advanced Very High Resolution Radiometer (AVHRR) observations.

In the context of the data flow in a processing system, one can consider the relationships portrayed in Figure 1, where DSL = digital signal level, L^* = apparent radiance at the sensor, DC = digital counts, ρ^* = apparent reflectance at the sensor, and ρ = surface reflectance. The DSL refers to raw data recorded by the imaging sensor system and the DC refers to digital data stored on the image product generated by the processing system. The DSL to L^* step (Figure 1) is radiometric sensor calibration. The L^* to ρ step is atmospheric correction. The L^* to ρ^* step is a conversion to reflectance, which is essentially the radiance normalized with respect to the solar irradiance at the sensor.

It is known that NDVI(DSL) is to be avoided if possible because of temporal changes in the uncalibrated DSLs (Teillet and Holben, 1994), although many data sets have been formed over the years using this variable. Ultimately, the best representation of NDVI is NDVI(ρ) because it is a function of the reflectance of vegetation at the surface, without extraneous effects due to changing sensor calibration and atmospheric conditions. A remaining difficulty with the current state-of-the-art is the role of directional reflectance effects on NDVI and the temporal compositing methodologies.

The calibrated and atmospherically corrected NDVI(ρ) will differ from the top-of-the-atmosphere values NDVI(L^*) and NDVI(ρ^*). Moreover, these last two values will also differ because the solar irradiance at the sensor will not be the same in the red and near-infrared spectral bands.

NDVI values will also be a function of image product characteristics such as numerical representation in binary form for data storage and display purposes. Typically, the scaling between L^* and DC(L^*) will be a linear equation with multiplicative and additive coefficients. Thus, NDVI(L^*) and NDVI(DC(L^*)) will not be directly comparable. The relationship between ρ^* and DC(ρ^*), as well as between ρ and DC(ρ), will usually consist of a multiplicative scaling only, with no additive offset. For example, 10-bit data running from 0 to 1023 can be used to represent reflectances from 0 to 102.3 percent by means of a scaling factor of 10. This means that NDVI(ρ) = NDVI(DC(ρ)) and NDVI(ρ^*) = NDVI(DC(ρ^*)). Currently, many users are working with calibrated data that have not been atmospherically corrected. The better choice in such cases is to use NDVI based on ρ^* rather than L^*. This is because apparent reflectance, ρ^*, is a less sensor-specific variable than apparent radiance, L^*, and because the equivalence between NDVI(ρ^*) and NDVI(DC(ρ^*)) provides a computational advantage.

The scope of the investigation reported in the balance of this paper is limited to vegetation indices defined in terms of atmospherically-corrected surface reflectances in the red and near-infrared spectral bands.

3. DATA SETS AND METHODOLOGY

The AVIRIS data used for this NDVI study were acquired over two forested areas in the Kootenay Valley near Invermere in Southeastern British Columbia on August 14, 1990. Available ground reference information includes a geographic information system (GIS) of the test sites on a 1:20,000 scale with digital elevation models, forest inventory maps, and forest attribute information.

Specific target types as listed in Table 1 were selected from the AVIRIS imagery on the basis of the forest inventory maps. For this purpose, it was necessary to register the forest cover maps to one of the AVIRIS scenes in order to definitely delineate the target areas (polygons) while the polygon boundaries in the other scene could be visually determined for the targets selected. This map-to-image registration resulted in a root-mean-square error of ± 1.50 pixels in the pixel direction and ± 0.95 pixels in the line direction using the nearest neighbour resampling technique. The selected target areas are located in flat terrain and vary in size between 0.3 x 0.3 km^2 and 2.0 x 3.0 km^2. This means that for ground instantaneous fields-of-view (GIFOVs) of 500 and 1100 m, the target area may consist of a mixture of different target types (Table 1).

Figure 2 summarizes the data processing flow. The 20-m AVIRIS data were spatially degraded to resolutions of 60, 100, 260, 500, and 1100 m by averaging blocks of pixels within selected vegetated areas. This approach to spatial degradation was felt to be appropriate for examining the behaviour of NDVI as a function of varying scale and spectral bandwidth. Therefore, more sophisticated techniques such as those based on modulation transfer functions (Justice et al., 1989) were not used. The spectral resolution simulation was carried out by convolving the 10-nm AVIRIS radiance data with Gaussian-like spectral response profiles in the red and near-infrared to generate a series of generic bandwidths: 30, 50, 100, and 150 nm FWHM (full width at half maximum). The red and near-infrared bands were centred at 660 nm and 850 nm, respectively (Figure 3). Sensor-specific bands such as those for SPOT Haute Résolution Visible (HRV), Landsat Thematic Mapper (TM), and NOAA AVHRR were generated using their actual spectral response profiles. Simulated bands were also generated for EOS Moderate-resolution Imaging Spectroradiometer (MODIS) and Envisat Medium-Resolution Imaging Spectrometer (MERIS) using Gaussian-like profiles (Table 2). These data were corrected for atmospheric effects using a modified version of the 5S atmospheric code (Tanré et al., 1990; Teillet, 1989; Teillet and Santer, 1991) and the input parameters given in Table 3. Finally, NDVI values were computed on the basis of the red and near-infrared spectral bands for the simulated bandwidth set at the different spatial resolutions.

It is clear that most of the spatial resolution combinations for the known sensor types are fictitious. Nevertheless, these combinations are included in the results for completeness and because they provide useful information for the acquisition of validation data sets based on ground-based and aircraft sensor data. In the spectral dimension, the NDVI results were generated on the basis of both equal and differing bandwidth combinations for the red and near-infrared spectral bands.

4. RESULTS FOR NDVI

Figure 4 illustrates the main results for three target types: spruce, yellow pine, and mixed coniferous forest (Douglas fir, larch, lodgepole pine), which are seen to have distinct NDVI amplitudes. In all three cases, varying the spatial resolution from 20 m up to 1100 m has no effect on NDVI and the curves for the six spatial resolutions are almost superimposed. In the spectral domain, NDVI clearly decreases as the spectral bandwidth of the bands making up the vegetation index increases from 10 nm up to 150 nm. The decrease is relatively small from 10 nm to 50 nm, but is considerably steeper for spectral bandwidths wider than 50 nm. The same decreasing NDVI behaviour is observed in the sequence of specific sensors from MERIS, to MODIS, to TM, to HRV, to AVHRR. Note that these specific sensor cases are individual ones and that connecting lines are used in Figures 4 and 5 for visualization purposes only.

Figure 5 shows the NDVI results for the other target types involved in this study. The spectral character of these results is much the same as that of the three target types already discussed, but changes in the spatial resolution do have an effect for the four classes shown in Figure 5. For the aspen/spruce stand and for the Douglas fir stand, the NDVI drops significantly for GIFOVs greater than 260 m and 500 m, respectively. For the heterogeneous target made up of clear cut and forested terrain, the NDVI decreases markedly when the spatial resolution gets too high, i.e., finer than 260 m in this case. For the clear cut target type, the NDVI increases when the spatial resolution is degraded, with the exception of the 260-m case, which is indistinguishable from the 20-m and 60-m cases. This situation for the clear cut target area arises because of some scattered mixed vegetation near, but not at, the centre of the clear cut. All of these results are consistent with what one would expect as the GIFOV is varied relative to the size of land cover elements such as the forest stands.

For the forestry-related target categories in this investigation, Figure 6 emphasizes how changes in NDVI, whether up or down, tend to occur at scales on the order of 260 m to 500 m. The MERIS case is shown in Figure 6, but the other sensors and spectral resolutions all give similar results.

If the spectral resolutions in the visible, red spectral band and the near-infrared spectral band are varied separately, one finds that NDVI is considerably more sensitive to changes in the red spectral band. The contour plot in Figure 7 illustrates this point for the spruce stand at 260-m spatial resolution. Contour plots for the other spatial resolutions and target types have very similar characteristics.

Elvidge et al. (1995) have shown that narrow-band vegetation indices can be affected almost as much as broad-band indices by background effects due to rock and soils in the case of discontinuous plant canopies. In such cases, better estimates of percent plant cover and leaf area index can be obtained using continuous narrow-band derivative-based vegetation indices (Elvidge et al., 1994). Thus, the advent of readily-available imaging spectrometer data from satellite platforms will likely give rise to the creation of significantly improved vegetation indices with wider applicability.

5. NDVI DEPENDENCE ON LOCATION AND WIDTH OF THE NEAR-INFRARED SPECTRAL BAND

The spectral reflectance of vegetation typically increases from a minimum due to chlorophyll absorption, at a relatively fixed location of about 660 to 665 nm, to a maximum reflectance on the near-infrared plateau. The spectral character of this latter region, which generally occupies the wavelength range from approximately 750 to 1300 nm, varies with vegetation type and condition. The near–infrared plateau region is also significantly affected by atmospheric gas absorption when remotely sensed from satellite and aircraft altitudes. Absorption due to atmospheric water vapour is the main contributor to this effect, the oxygen absorption line at 760 nm being a spectrally localized and relatively stable feature.

Although crops, forests, and other types of vegetated ground cover tend to have different degrees of amplitude variations in the plateau region (largely due to liquid water in the plants, canopy architecture and light scattering considerations), most types of healthy vegetation exhibit first a gradually increasing and then a more variable decreasing reflectance with increasing wavelength in this region. Consequently, for placement of the near-infrared spectral band for NDVI use, emphasis generally has been placed on the shorter wavelengths in this range, more specifically between the top of the red edge around 780 nm and the strong atmospheric water vapour absorption features that occupy the 880 to 1000 nm region. A weaker atmospheric water vapour absorption feature is also present in the 780 to 860 nm region. Thus, initial consideration is given to placing the near–infrared spectral band at 780 nm or between 860 and 880 nm, and making the band fairly narrow. However, with a reasonable atmospheric correction, constraints on the location and width of this band are likely to be less severe. In order to explore these issues, results were generated across the spectral range from 780 to 1000 nm on 10-nm intervals. The process was carried out for both a reasonable atmospheric correction and an inadequate one based on half the proper water vapour content (namely, 1.5 g cm^{-2} compared to 3 g cm^{-2} in this case).

The main results for a spatial resolution of 260 metres are presented in Figure 8, which includes plots of NDVI as a function of near-infrared wavelength location and spectral bandwidth for the three forest target types selected from the AVIRIS imagery (Table 1): (1) mixed coniferous forest (Douglas fir, larch, and lodgepole pint); (2) a mixture of clear cut areas and pine stands; and (3) clear cut. Except for the known sensor bands, all results are for a 10-nm FWHM red spectral band.

It appears that, with a reasonable correction for atmospheric water vapour absorption, the placement of the near-infrared spectral band for NDVI use is not critical. Longer wavelengths in the spectral region examined appear to be better, but the shorter wavelengths are also acceptable if the spectral band is no wider than 50 nm (FWHM). The AVHRR NDVI values are lower because of the width of the red spectral band (113 nm compared to the 10-nm width of the simulated red band). The MERIS results are very good, as they were designed to be for vegetation monitoring. The MODIS results are reasonably good as well but not as good as the MERIS ones, in this case largely because of the wider red spectral bandwidth for MODIS (50 nm). The results in Figure 8(b) were generated in order to assess the impact of inadequate atmospheric correction on the location and width of the near-infrared band. A comparison of these results with those in Figure 8(a) leads to the following observations:

(1) the spectral bandwidth should be less than 50 nm (FWHM) if errors in NDVI are to be no greater than approximately 0.02;

(2) the optimum wavelength location is at 865 nm;

(3) there are usable wavelength locations in the 840 to 880 nm range, although the 850 to 880 nm range would be safer to use;

(4) a narrow spectral band in the 780 to 810 nm range appears to be acceptable, although NDVI values will be less than those at longer acceptable wavelengths;

(5) a narrow spectral band at 1000 nm would be acceptable, but that wavelength region may be susceptible to detector sensitivity problems and to other atmospheric effects that have not been addressed (Ahern et al., 1991);

(6) the curves in Figure 8(b) for spectral bandwidths of 100 and 150 nm (FWHM) appear to be relatively smooth, but their amplitude is depressed compared to the proper atmospheric correction cases.

6. RESULTS FOR OTHER VEGETATION INDICES

While an exhaustive analysis of the many different vegetation indices that have been developed is beyond the scope of this study, additional results were generated for several vegetation indices that make straightforward use of atmospherically corrected red and near-infrared spectral bands. The ratio-vegetation index is defined as RVI = NIR/RED (Jordan, 1969; Pearson and Miller, 1972) and the difference vegetation index is defined as DVI = NIR - RED (Clevers, 1986). The soil-adjusted vegetation index is given by SAVI = 1.5 (NIR - RED)/(NIR + RED + 0.5) (Huete, 1988). Qi et al. (1994b) proposed a modified version defined as

$MSAVI = 0.5 [2 NIR + 1 - ((2 NIR + 1)^2 - 8 (NIR - RED))^{1/2}]$. In a relative sense, results for all of the vegetation indices examined exhibit very similar behaviour as a function of spectral bandwidth and spatial resolution. Figure 9 provides an example for the mixed coniferous forest target. This is to be expected given the mathematical similarity of these indices (Crippen, 1990).

7. CONCLUSIONS

For the forestry-related targets examined in this study, an increase in the bandwidths of the red and near-infrared spectral bands used to form NDVI leads to a decrease in NDVI values, with most of the change attributable to the bandwidth of the red spectral band. This result is much as one would expect given the limited spectral width of the chlorophyll absorption well of vegetation at red wavelengths. The result emphasizes the point that, even if spectral data from different sensors are radiometrically calibrated and atmospherically corrected, the NDVI values derived from them are not necessarily comparable. Moreover, for an optimum NDVI definition, the red spectral band should be as narrow as possible and less than 50 nm wide (FWHM). Even the Landsat TM and SPOT HRV sensors are sub-optimum in this respect. Although MERIS and MODIS datasets will likely be used to generate new and improved vegetation indices, NDVI values derived from these forthcoming data sets would be close to being optimum spectrally.

The impact of the location and width of the near-infrared spectral band used to form NDVI has been examined. For the forestry-related targets in this study and for a spatial resolution of 260 nm, the location of the spectral band is not that critical, provided that the bandwidth is no more than 50 nm (FWHM) and the atmospheric correction is good. To allow for the possibility that the correction for atmospheric water vapour absorption is in error, the optimum band placement is in the 850 to 880 nm wavelength range and the spectral bandwidth should be less than 50 nm (FWHM) if errors in NDVI are to be within 0.02.

Changes in NDVI due to differences in spatial resolution depend on the nature of the land cover, particularly the spatial extent of forest stands and clear cuts in this study. For the forested region in Southeastern British Columbia, distinct changes in NDVI occur at scales on the order of 260 to 500 metres, regardless of spectral band characteristics.

Compared to NDVI, other vegetation indices examined (SAVI, MSAVI, RVI, and DVI) were found to have very similar behaviour as a function of spectral bandwidth and spatial resolution.

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Table 1. Targets selected from the AVIRIS scenes. The simulated GIFOVs (Ground Instantaneous Field-of-View) that completely enclose the targeted polygons are indicated, where the set of GIFOVs includes 20, 60, 100, 260, 500 and 1100 metres.

	GIFOV Cases		Target Characteristics			
Target Type (Symbols)	Within Polygon Boundaries	Outside Polygon Boundaries	Crown Closure (%)*	Age (years)*	Height (m)	Remarks
Spruce (S)	= 500 m	1100 m	80	130	11-20	
Yellow pine (YP)	= 260 m	500 m, 1100 m	30	130	11-20	
Douglas fir (F)	= 260 m	500 m, 1100 m	30	50	11-20	Minor species; yellow pine
Aspen/spruce (AS)	= 260 m	500 m, 1100 m	40	130	11-20	
Douglas fir/larch/ Lodgepole pine(FLP)	= 1100 m	--	20	70	= 10	Immature stand
Clear cut (CC)	= 1100 m	--	--	--	--	Logged in 1981-83
Clear cut/ forested area (CF)	--	= 1100 m	50	50	20	Mixture between clear cut areas and pine stands

* Averaged values

Table 2. Generic and sensor-specific band characteristics used for calculation of the surface reflectance in the red and near-infrared bands.

	Red Band			Near-Infrared Band		
Sensor	Band #	Centre Wavelength (nm)	Bandwidth (nm)	Band #	Centre Wavelength (nm)	Bandwidth (nm)
Landsat TM	3	661	66	4	838	121
SPOT HRV	2	653	64	3	840	101
NOAA AVHRR	1	633	113	2	847	229
EOS MODIS	1	645	50	2	858	35
Envisat MERIS	7	665	10	12	880	10
Generic 10		660	10		850	10
Generic 30		660	30		850	30
Generic 50		660	50		850	50
Generic 100		660	100		850	100
Generic 150		660	150		850	150

Table 3. 5S input parameters.

Parameter	Area 1	Area 2
Atmospheric model	Mid-latitude summer	Mid-latitude summer
Aerosol model	Continental	Continental
Date of overpass	August 14, 1990	August 14, 1990
Solar zenith angle	35.87 degrees	35.69 degrees
Solar azimuth angle	179.49 degrees	182.73 degrees
Sensor zenith angle	Variable	Variable
Sensor azimuth angle	30.3 or 210.3 degrees	32.68 degrees
Ground elevation*	Variable	0.900 km
Sensor altitude above sea level	19.850 km	19.844 km
Horizontal visibility	50 km	50 km

* Several targets were extracted from Area 1, whereas only one target was extracted from Area 2. In all cases, selected targets were located in flat terrain.

Figure 1. Different radiometric representations of NDVI illustrated in the context of possible data processing flows.

Figure 2. Processing data flow for the NDVI study, where RSRP = relative spectral response profile.

Figure 3. Schematic representation of red and near-infrared spectral bandwidths (FWHM) for (a) generic and (b) specific spectral band cases. The plotted spectrum represents a typical reflectance for vegetated surfaces.

Figure 4. NDVI study results emphasizing the spectral domain for spruce (S), yellow pine (YP), and fir/larch/pine (FLP) stands for the indicated GIFOVs. The sensor cases are the generic spectral bands with full width at half-maximum of 10, 30, 50, 100, and 150 nm, and the specific sensors MERIS (ME), MODIS (MO), TM, HRV (HR), and AVHRR (AV). Connecting lines between sensor cases are used for visualization purposes only.

Figure 5. NDVI study results emphasizing the spectral domain for the indicated target categories, where the sensor cases and the different line types indicating GIFOV cases are as defined in Figure 4.

Figure 6. NDVI study results emphasizing the spatial domain, for the MERIS case as an example.

Figure 7. NDVI study results for independently varying spectral resolutions in the RED and near-infrared (NIR) spectral bands, for the spruce stand at 260-metre spatial resolution.

Figure 8. NDVI results are plotted as a function of centre wavelength location (x-axis) and bandwidth (different curves as noted) for the near-infrared spectral band. Special symbols indicate the results for AVHRR (centred at 847 nm; filled triangles), MODIS (centred at 858 nm; filled circles), and MERIS (centred at 880 nm; filled squares). The left-hand and right-hand figures are for reasonable and erroneous atmospheric corrections, respectively. For both figures, the upper, middle, and lower sets of curves are for the (1) fir/larch/pine, (2) mixture of clear cut and pine, and (3) clear cut target types, respectively.

Figure 9. Vegetation index results as a function of spectral bandwidth for the mixed coniferous target (fir/larch/pine), where the sensor cases and the different line types indicating GIFOV cases are as defined in Figure 4.