Data Fusion of Landsat TM and IRS Images in Forest Classification

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Abstract.—Data fusion of Landsat TM images and Indian Remote Sensing satellite panchromatic image (IRS-1C PAN) was studied and compared to the use of TM or IRS image only. The aim was to combine the high spatial resolution of IRS-1C PAN to the high spectral resolution of Landsat TM images using a data fusion algorithm. The ground truth of the study was based on a sample of 1,020 relascope plots. The results indicated that compared to use of TM or IRS image only, the data fusion increased the classification accuracy of four tree species classes, three age classes, and their 12 combined stand classes. However, the classification using IRS image alone was not better than that using TM images only.

Satellite remote-sensing data can be related to a number of stand-level forest characteristics (Ahern *et al.* 1991; Cihlar *et al.*; 1991, Cook *et al.* 1989; Häme 1984; Poso *et al.* 1984, 1987). These relationships can be used in forest inventories (Franklin 1986, Ripple *et al.* 1991, Sader *et al.* 1989). Small position distortions due to high orbit altitude and large area coverage (e.g., Landsat TM 185 x 185 km) are properties that can also be exploited in forest inventory. However, the spatial resolution of satellite remote-sensing data is too poor to fully capture forest stand parameters with high levels of accuracy (Jupp *et al.* 1988, 1989).

As new satellites are launched, the spatial resolution of images has increased to 5 m in IRS-1C (PAN). In the near future, the resolution will be even 1 m in CARTERRA-1, for example. These new satellites combine high spatial resolution with large area coverage and small positional distortion. Unfortunately, these high spatial resolution data are registered only for the panchromatic channel (e.g., IRS-1C 0.5 - 0.75 µm), while vegetation is interpreted most reliably from multispectral images. Thus, more and more attention has to be paid to how to combine the advantages of both data sources by techniques known as data fusion or data merging. The aim is to combine high spatial resolution of one sensor (e.g., IRS-1C PAN) to the high spectral resolution of another sensor (e.g., Landsat TM).

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A great deal of effort has been put into improving remote sensing data for visual image analysis (Cliche *et al.* 1985, Haydn *et al.* 1982). Jaakkola and Hagner (1988) obtained promising results by merging SPOT-1 HRV images to panchromatic aerial photographs. They used the combined images mainly for visual interpretation. Numerical analysis for merged images has also been studied widely (Pradines 1986, Price 1987). Liuha (1996) presented a good overview of these methods.

In the present study, Landsat TM was merged with IRS-IC (PAN). Landsat TM was selected to provide the spectral information, since in various studies it had recorded highly relevant information for vegetation inventories. The present Indian Remote Sensing panchromatic (IRS-1C PAN) image provides 5-m spatial resolution and was thus chosen to produce spatial data. The main objective of the study was to improve classification accuracy of forest stands using image data fusion techniques. The emphasis was put on numerical image analysis with consideration of visual interpretation. The original and merged images were compared. Forest stand was a classified variable defined by main tree species and stand age.

MATERIAL

The Hyytiälä area, located in southern Finland (61°50'N, 24°18'E), was selected for this study. The area was characterized by the presence of mineral soil and pure and mixed coniferous forests of Scots pine *(Pinus sylvestris)* and Norway spruce *(Picea abies)* with managed forest fragments of various ages and soil fertility types. The terrain has low, gently sloping hills, and the average elevation is 155 m above sea level with a range from 140 to 185 m.

The field data consisted of 232 systematically located (100-m x 100-m grid) plots taken during summer 1995 and 788 plots taken in 1989, which were updated to the 1995 level. The total size of the area was about 300 ha.

Tree, site type, and vegetation information were measured on all plots using fixed-area relascope plots (radius of 12.5 m). For a more detailed description of the sampling design and field measurements, readers are referred to Wang (1996). The field plots were geo-referenced using GPS with differential correction and six receiving channels.

Satellite images used included Landsat TM channels 1 - 5 and 7 taken on June 1, 1995, and an Indian Remote Sensing (IRS) panchromatic channel taken on August 24, 1996. The IRS was launched on December 28, 1995, and it revisits the same orbit every 24th day. The orbit altitude of the IRS with three sensors is 817 km, and the sensor PAN provides panchromatic image with spatial resolution of 5 m and spectral resolution of 0.5 – 0.75 μm.

The study area was located in the center-lower part of the IRS and TM images. The IRS panchromatic image and TM images were rectified to the Finnish uniform co-ordinate system using affine transformation with more than 12 control points. The rectification accuracy was 0.58 pixels in the columns and 0.33 pixels in the rows for the TM images, and 1.04 pixels in the columns and 1.51 pixels in the rows for the IRS image. The spatial resolution of the TM image was 30 m, and the spatial resolution of the IRS image was 5 m.

The classification accuracy of the images was computed using a special classification variable, forest stand, by taking into account main tree species and ages of the stand. The main tree species (> 55 percent basal area) included four classes (pine, spruce, deciduous, and mixed), and stand average age consisted of three classes (young stands: < 16 years, middle-aged stands: 16-65 years, and mature stands: > 65 years). Thus, the total number of possible forest stands was 12; however, only 11 classes actually existed in the collected field material (table 1).

The 232 field sample plots measured in 1995 were used to provide ground truth for image classification. The 788 field plots measured in 1989 were updated to the level of 1995 and applied to test the classification accuracy of the forest stands. The data were updated because no independent test samples at the same measurement time were available for the analysis.

METHODS

Study Outline

The study can be divided into three parts: data fusion of the IRS panchromatic channel and six TM channels, classification of sample plots into forest stands, and accuracy assessment of classification. The ER Mapper system (ER Mapper 1995) was applied to the data fusion and unsupervised classification of images by the K-means algorithm. The strata from the unsupervised classification and the field data were combined to derive class estimates for the forest stands. The accuracy of the classification obtained was assessed plotwise using a remote sensing-based forest inventory and monitoring system called SMI, developed by the Department of Forest Resource Management at the University of Helsinki (Poso *et al.* 1984, 1987, 1990; Waite 1993; Wang *et al.* 1997). Figure 1 shows an outline of the study.

Data Fusion

The original images were rectified to the Finnish uniform co-ordinate system (called YKJ) and saved in the data

Table 1.—*List of forest stands used and the respective numbers of field plots*

Main tree species	Age-class	Forest stand: Class number	Forest stand: Description	Number of field plots
Pine	1	1	young pine	17
Pine	2	2	middle-aged pine	206
Pine	3	3	mature pine	250
Spruce	2	5	middle-aged spruce	103
Spruce	3	6	mature spruce	269
Deciduous	1	7	young deciduous	20
Deciduous	2	8	middle-aged deciduous	54
Deciduous	3	9	mature deciduous	6
Mixed	1	10	young mixed	15
Mixed	2	11	middle-aged mixed	26
Mixed	3	12	mature mixed	54
Total				1,020

Data fusion

The IRS panchromatic and 6 TM channels

Transformation of images to the ER Mapper format

Merging the images
1) selection of 3 TM channels
2) histogram transformation or Gaussian equalization
3) data fusion by the Brovey-transformation

Unsupervised classification

Setting parameters: e.g.
- channels
- number of classes
- iterations

Classification by K-Means algorithm

Results for each pixel based on window

Accuracy assessment

Division of sample plots to training and test data sets

Calculation of the forest stand mode for each image class using the training data set

Deriving forest stand for each test set sample plot

Accuracy assessment of the test data set
- image class versus field information

Figure 1.—*An outline of the study.*

form used in the ER Mapper. A seven-channel virtual data set containing six TM channels and the IRS panchromatic image was created. The ratio method was chosen for data fusion of TM channels and IRS, because it was known to retain radiometric information. The ratio method is especially suitable for images that correlate strongly (Liuha 1996, Pradines 1986). In the present study, pairwise image correlation coefficients varied between 0.59 - 0.80, regarded as being strong enough. The ratio is a straightforward method to combine spectral information of Landsat TM to the spatial information of the IRS (fig. 2).

When creating a suitable photo for visual interpretation, one should take into consideration that the human eye is sensitive to small changes in structure and to overall color patterns. This indicates that high variability information should be shown as intensity, whereas overall patterns should be shown in color. An algorithm called the Brovey transformation data fusion was created in the ER Mapper using a formula for combining the TM images in red, green, and blue, and the IRS panchromatic image in intensity, further sharpened using a histogram transformation and Gaussian equalization to the IRS image. During this processing, the ER Mapper data remain in the original resolutions of the TM images and the IRS image. When the Brovey transformation algorithm was used for classification, the operation was made based on TM image pixels (30 x 30 m) and the corresponding size window (6 x 6 pixels) of IRS panchromatic image pixels (5 x 5 m). However, the resolution of the classification result image was the same as that of the IRS panchromatic image. The outcome was an image resembling a false color aerial photo.

To create a merged image, one can choose any combination of the TM channels. To present the formulas needed for calculation, an example is given. When TM channels 3, 2, and 1, are selected to be displayed as red, green, and blue, and the IRS panchromatic image is taken in intensity layer, the transformation can be expressed as formulas (1-3):

$$B = \frac{TM_1 * IRS_{PAN}}{TM_1 + TM_2 + TM_3} \tag{1}$$

$$G = \frac{TM_2 * IRS_{PAN}}{TM_1 + TM_2 + TM_3} \tag{2}$$

$$R = \frac{TM_3 * IRS_{PAN}}{TM_1 + TM_2 + TM_3} \tag{3}$$

There are many possible combinations of TM channels.

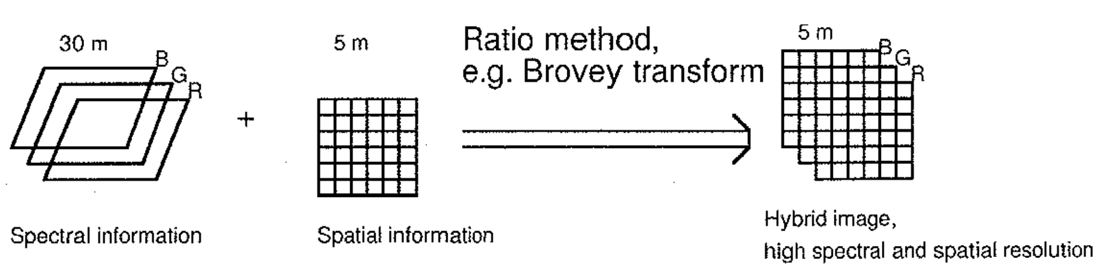

Figure 2.—*Data fusion by e.g. Brovey transform.*

However, the Brovey transformation algorithm was used in this study as a method of data fusion to select and combine TM channels with the IRS panchromatic image so that the resulting image would be simultaneously interpretable visually and numerically. Due to visual interpretation, certain factors had to be taken into account in the fusion process. TM channels are sensitive to certain spectral windows; for example, channel one registers wavelengths 0.45 - 0.52 μm, which the human eye senses as blue. So, for a merged image, the blue layer should preferably be TM channel one, the green channel two, and the red channel three or four. The following combinations were also tested here:

Layer	TM ch	TM ch	TM ch	TM ch	TM ch	TM ch
R	3	4	5	5	5	7
G	2	3	3	4	4	4
B	1	2	1	1	2	1

Either TM channel 3 or 4 was present in all combinations because these channels are known to perform well when estimating biomass or vegetation. For example, the normalized vegetation index (NVDI = (TM4-TM3) / (TM4 + TM3)) has been used in the assessment of forest biomass and other ecological characteristics by remote sensing. (Campbell 1987, Cihlar *et al.* 1991, Sader *et al.* 1989).

Unsupervised Classification

An unsupervised classification of the whole image produced by the Brovey transformation was performed. The classification of each pixel was based on a window of 30 x 30 m for the merged images with resolution of 5 m. For comparison, an unsupervised classification of the TM channel combinations or the IRS panchromatic image only was also carried out. In the unsupervised classification, one of the most important input parameters was number of classes. The processed image area mainly consisted of forested land, agricultural land, waste land, built-up area, lakes, and roads. Forested land was further classified into forest stands, and the maximum number of those classes was 11. Thus, the number of classes for the classification of the processed image area was set to 20. In addition, the default values of the ER Mapper for the number of iterations (9999) and unchanged percent (98 percent) were used as the respective input parameters.

Plotwise Accuracy Assessment

The plotwise accuracy of the classification was assessed using the SMI system. Although the whole image area also included other land-use classes, the emphasis for the assessment was put upon the classification of the forest stands shown in table 1. Field data were divided into two parts: (a) training data set (232 sample plots), and (b) test data set (788 sample plots). The training data set was used to define forest stand for each image class. This was done simply by attaching the most frequent forest stand class in the field to each image class. The forest stands of the training plots and these image classes were combined resulting in an image with known class contents. The estimate of forest stands for a sample plot in the test data set was derived using the most frequent forest stand class within the window of 30 x 30 m around the plot center in the result image of 5-m resolution.

Assessment of classification accuracy was based on an error matrix, in which the estimated and observed stand classes at the test plots were compared. In the error matrix, the diagonal elements show the number of correctly classified observations. The percentage correct, which is mostly used to evaluate the estimation accuracy, is calculated by dividing the number of correctly classified observations by the total number of observations. The percentage correct shows only the relative effectiveness of the classification; it does not account for the entire error matrix, i.e., the estimation accuracy of each individual class. Cohen (1960) improved the analysis of an error matrix and developed a new estimator referred to as the Kappa value. Kappa (Formula 4) is a measure for quantifying the agreement between estimated and observed classes.

$$K = \frac{observed - \exp ected}{1 - \exp ected} \quad (4)$$

Observed indicates the overall percentage correct value and *expected* indicates the estimate of chance agreement. *Expected* is calculated by first assigning the products of the row and column totals to each cell of the matrix, after which the diagonal values are summed and divided by the grand total of the products. A Kappa value of 1.0 indicates a perfect, and 0 or less, a poor classification result. Values near zero imply that the classification is not significantly better than a random assignment of observations to classes.

RESULTS

The resolution difference between IRS-1C PAN and Landsat TM channel 4 is shown in figure 3. There is also a merged image that has spectral information for TM channels 2, 3, and 4 presented as blue, green, and red. To the resulting image, IRS-1C PAN was added as intensity information. The image can be regarded as being more suitable for visual interpretation than TM or IRS image alone. However, its suitability to digitizing, compartment boundaries, for example, was not tested.

The numerical analysis started with the unsupervised classification of the merged images. The resolution of the classified images increased from 30 by 30 m of TM images to 5 by 5 m of the IRS-1C PAN image. The classified images should thus be more detailed, and they should contain more information. Figure 3 gives an example of one merged image (TM4, TM3, TM2, IRS) classified to the present age classes.

The plotwise accuracy was assessed calculating error matrices between the image classification results and field measurements of the forest stands. The performances of the merged images, TM and IRS-1C PAN images, were compared by percentage correct and Kappa values (table 2).

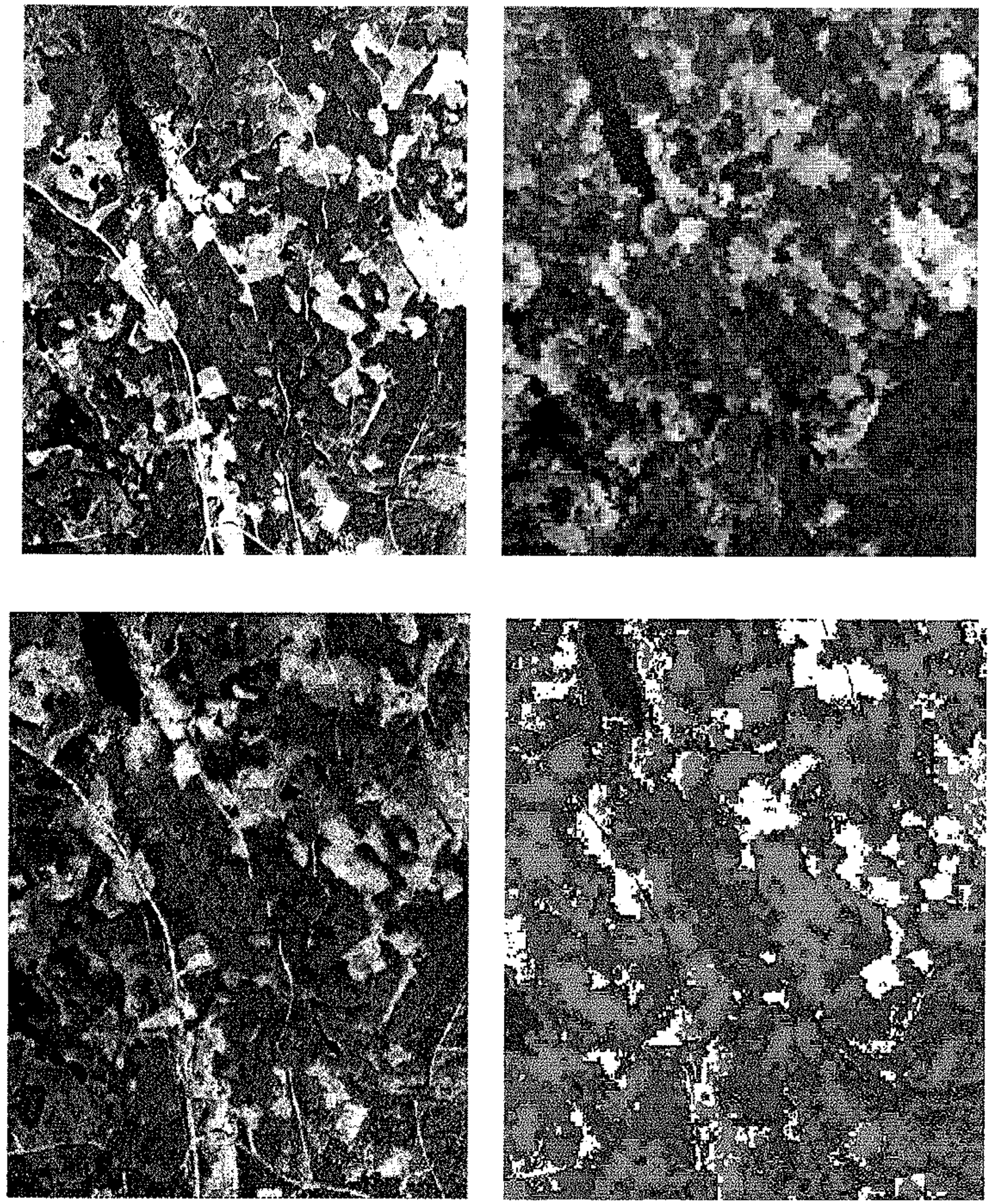

Figure 3.—*IRS-1C PAN (above left), Landsat TM4 (above right). Merged image of TM2 - blue, TM3 - green, TM4 - red and IRS-1C PAN - intensity (below left). Below right same image classified. Blue - water, Red - mature stands, Green - middle-aged stands, Yellow - young stands, and Magenta - others. These colors corresponding following grays: blue = black, red = dark gray, green = light gray, yellow = white, magenta = light dark gray.*

Table 2.—*Plot wise classification accuracy for forest stands*

Data fusion of TM and IRS			TM or IRS		
Image	Percentage correct, %	Kappa value	Image	Percentage correct, %	Kappa value
		4 tree species classes			
TM432_I	56.7	0.277	TM432	50.7	0.219
TM531_I	**70.2**	**0.464**	TM531	**67.3**	**0.415**
TM541_I	67.6	0.435	TM541	66.6	0.413
TM741_I	46.2	0.019	TM741	59.6	0.303
			IRS	59.3	0.284
		3 age classes			
TM432_I	**68.5**	**0.356**	TM432	60.1	0.116
TM531_I	56.5	0.201	TM531	57.2	0.180
TM541_I	65.4	0.303	TM541	60.0	0.093
TM741_I	64.3	0.230	TM741	**62.7**	**0.278**
			IRS	61.0	0.206
		12 forest stands			
TM432_I	42.6	0.239	TM432	33.8	0.130
TM531_I	43.5	0.240	TM531	**43.5**	**0.229**
TM541_I	**46.3**	**0.283**	TM541	39.6	0.198
TM741_I	40.4	0.209	TM741	40.2	0.205
			IRS	40.9	0.189

For four tree species classes, the percentage correct was 46.2 - 70.2 percent and the Kappa value was 0.019 - 0.464 when merged images were used. If the TM channels alone were used, the accuracy decreased slightly: 50.7 - 67.3 percent and 0.219 - 0.415 Kappa value. When the IRS image was used alone, 59.3 percent correct and 0.284 Kappa value were obtained. The merged image of TM channels 5, 3, and 1 and IRS gave the best classification accuracy of 70.2 percent correct and 0.464 Kappa value.

For three age classes, the merged images were again slightly better with 56.5 - 68.5 percent correct and 0.201 - 0.356 Kappa value. In the TM channels alone, the corresponding results were 57.2 - 62.7 percent correct and 0.093 - 0.278 Kappa value, and in IRS panchromatic image only, 61.0 percent correct and 0.206 Kappa value.

Finally, 12 forest stand classes were estimated, and it was observed that different combinations of channels led to results having remarkably less variation than species groups or age classes. The merged images were again a bit better with 40.4 - 46.3 percent correct and 0.209 - 0.283 Kappa value. For the TM images alone, the results were 33.8 - 43.5 percent correct and 0.130 - 0.229 Kappa value, and for the IRS image only, 40.9 percent and 0.189.

The IRS panchromatic image provided almost as good a result as TM channels only when estimating age class. It received a 61.0 percent correct compared to 62.7 percent obtained by the best TM combination. With 12 forest stands the difference was a bit larger, and tree species groups' recognition with IRS led to the widest gap to TM.

For all studied combinations except the two—TM741_I for tree species and TM531_I for age classes—combining IRS with TM gave better classification accuracy. The improvement varied from 0.2 to 16.6 in percent correct and from 0.004 to 0.343 in Kappa value. In most cases the relative increase was more than 10 percent.

The following error matrix (table 3) shows the results of tree species detection using the best merged image (TM5, TM3, TM1, IRS). The percentage correct is promisingly good, 70.2 percent. One problem with the method is that one can easily notice the tendency in image classification towards dominating species in the study area. According to the image classification, there are only coniferous species, i.e., pine and spruce. Deciduous and mixed stands almost always contain some pine and spruce, which makes the classification more difficult. Four sample plots of test data were classified to a stratum without any field information in the modeling data set.

According to definitions, there were three age classes, but in the test data all sample plots except one were either middle-aged or mature stands. For the best combination (TM4, TM3, TM2, IRS), the percentage correct was 68.5 (table 4).

The third error matrix presents the classification accuracy of 12 forest stands (table 5). Percentage correct for middle-aged pine and mature spruce stands was more than 80 percent, whereas all the other forest stand classes remained less than 15 percent. Again the tendency towards pine and spruce can be seen, but there are also shifts from pine to spruce and vice versa. Another remarkable thing is that in one species group, age class seems to be difficult to estimate from the image.

Table 3.—*Error matrix for classification of tree species groups*

Ground truth	Classification result							
	Pine	Spruce	Deciduous	Mixed	Correct classfic.	Total	Percent	Kappa
Pine	**316**	51	0	0		367	86.1	0.174
Spruce	86	**234**	0	0		320	73.1	0.158
Deciduous	31	10	**0**	0		41	0	0
Mixed	31	25	0	**0**		56	0	0
Total	464	320	0	0	**550**	784	70.2	0.464

Table 4.—*Error matrix for classification of age classes*

Ground truth	Classification result						
	Young	Middle-age	Mature	Correct. classif.	Total	Percent	Kappa
Young	**0**	1	0		1	0	0
Middle-age	10	**184**	107		301	61.1	0.099
Mature	8	122	**355**		485	73.2	0.14
Total	18	307	462	**539**	787	68.5	0.356

Table 5.—*Error matrix for classification of forest stands*

Ground truth	Classification result													
	1	2	3	4	5	6	7	8	9	10	11	12	Total	P[1]	K[2]
1	**0**	1	0	0	0	0	0	0	0	0	0	0	1	0.0	0
2	0	**134**	6	0	0	23	1	3	0	0	0	0	167	80.2	0.088
3	1	108	**30**	0	0	58	2	2	0	0	0	0	201	14.9	0.022
4	0	0	0	**0**	0	0	0	0	0	0	0	0	0	0.0	0
5	1	23	6	0	**0**	48	2	4	0	0	0	0	84	0.0	0
6	1	32	5	0	0	**200**	0	0	0	0	0	0	238	84.0	0.128
7	0	0	0	0	0	0	**0**	0	0	0	0	0	0	0.0	0
8	0	22	3	0	0	7	3	**1**	0	0	0	0	36	2.8	0.001
9	0	1	0	0	0	3	0	1	**0**	0	0	0	5	0.0	0
10	0	0	0	0	0	0	0	0	0	**0**	0	0	0	0.0	0
11	0	2	2	0	0	9	0	2	0	0	**0**	0	15	0.0	0
12	0	11	0	0	0	28	2	0	0	0	0	**0**	41	0.0	0
												365			
Total	3	334	52	0	0	376	10	13	0	0	0	0	788	46.3	0.283

[1] P = Percentage correct, 2. K = Kappa value

DISCUSSION AND CONCLUSIONS

In the present study, the Brovey data fusion algorithm was used to merge TM and IRS images, and the plotwise accuracy of original and merged images was determined. It appears that resulting images can be interpreted visually without difficulties for many purposes in forestry. Numerical analysis was performed for classified variables, and it was shown that merged images slightly improved the classification result of forest stands compared to the TM or IRS alone.

Although the emphasis of this study was put upon numerical classification, the need for visual interpretation was considered. When TM channels were selected for the data fusion, the selection limitation was not avoided. In fact, the experiment of merging all six TM channels and the IRS image was also carried out and the results for numerical classification were not as good as expected, but similar to the best ones listed in table 2. The main reason may be that high correlation between these TM channels existed and adding more channels did not bring more and useful information.

Holopainen and Wang (1998) obtained better results with the same variables and same field material. They used digitized aerial photographs calibrated using empirical regression technique to minimize problems caused mainly by central projection of the photos. The percentage correct for classifying 12 forest stands was 49.2 compared to the 46.3 percent in the present study. Furthermore, Holopainen (1998) used imaging spectrometer (CASI) data to estimate the same forest stand classes and obtained a percentage correct of 62.2. When comparing the results, however, it must be stressed that the number of sample plots differed from the present study.

It appears that when using the combination of IRS and Landsat TM, one should not expect to gain major improvement in numerical classification of forest stands compared to the IRS or TM images alone. It can also be noted that with CASI and digitized aerial photos, it is possible to produce more accurate results than with merging TM and IRS images. Compared either to digitized aerial photos or an imaging spectrometer, the spatial resolution of IRS-1C PAN is poorer. The spectral resolution of Landsat TM is poorer than CASI data but better than digitized aerial photos. It remains uncertain which of these two is responsible for the poorer classification accuracy. In the near future, new satellites with better spatial resolution will be launched and these questions might be answered.

It is possible that merging the images does not bring additional information compared to the two original images. Another reason for the relatively small improvement obtained merging TM and IRS images may be the small variation among the forest stands in the study area. If the forest was more heterogeneous, the advantage of increasing spatial resolution of fused images may be greater. The usefulness of high resolution images would also be evident when trying to estimate tree-level forest characteristics. The increased spatial resolution of future satellite images may make also this objective possible.

One way to improve the results obtained here would be to reject the classification-based approach. Information on variation is lost when continuous variables are forced into discrete classes. In addition, the basic K-means algorithm labels the training plots only to one class. Similarly, variation is decreased when only the most frequent forest stand class in the field is used to define forest stand to each image class.

Furthermore, some of these problems could be avoided by using fuzzy information presentation instead of classical set theory. The use of fuzzy sets in accuracy assessment expands the amount of information that can be provided about the forest (Gopal and Woodcock 1994). The main idea of the method is that a unit can be a member of multiple categories; i.e., instead of choosing the most frequent stand class, the unit would be connected to several classes. Applying fuzzy technology is believed to lead to more accurate classification results compared to the traditional methods (Gopal and Woodcock 1994).

In Finland, the major forest owners (Enso, Metsähallitus, Metsäliitto, and UPM-Kymmene) are shifting toward systems where total inventories of forests are replaced by continuous updating of forest databases. Since these companies are managing their forests by compartments, one major issue concerning the reliability of an updated database is the correct location of the compartment boundaries. Numerical change detection has been studied widely in Finland. Häme (1991) found that by comparing temporally different Landsat TM image pairs for the same area, changes in forests, especially clearcut areas, can be detected. Häme also pointed out that changes for large areas are detected reliably; however, for small areas, accuracy is poor. Varjo (1993) found that positional errors of compartment boundaries when using numerical change detection could be even several pixels. Hyppänen *et al.* (1996) found digitized aerial photographs to be useful for detecting compartment boundaries of clearcut areas. However, high resolution satellite images or merged images could turn out to be more accurate than low resolution satellite images and more efficient than aerial photographs in performing visual and numerical change detection in forests.

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LITERATURE CITED

Ahern, F.J.; Erdle, T.; Maclean, D.A; Kneppeck, I.D. 1991. A quantitative relationship between forest growth rates and Thematic Mapper reflectance measurements. International Journal of Remote Sensing. 12: 378-400.

Campbell, J.B. 1987. Introduction to remote sensing. New York, London: The Guilford Press.

Cihlar, J.; St.-Laurent, L.; Dyer, J.A. 1991. Relation between the normalized difference vegetation index and ecological variables. Remote Sensing of Environment. 35: 279-298.

Cliche, G.; Bonn, F.; Teillet, P. 1985. Integration of the SPOT panchromatic channel into its multispectral mode for image sharpness enhancement. Photogrammetric Engineering and Remote Sensing. 51: 311-316.

Cohen, J. 1960. A coefficient of agreement for nominal scales. Educational and Psychological Measurement. 20: 37-46.

Cook, E.A.; Iverson, L.R.; Graham, L.R. 1989. Estimating forest productivity with Thematic Mapper and biogeographical data. Remote Sensing of Environment. 28: 131-141.

ER Mapper 5.0. 1995. Application, Reference, and Tutorial. Earth Resource Mapping Pty.Ltd.

Franklin, J. 1986. Thematic mapper analysis of coniferous forest structure and composition. International Journal of Remote Sensing. 7: 1287-1301.

Gopal, S.; Woodcock, C. 1994. Theory and methods for accuracy assessment of thematic maps using fuzzy sets. Photogrammetric Engineering and Remote Sensing. 60: 181-188.

Haydn, R.; Dalke, G.W.; Henkel, J.; Bare, J.E. 1982. Application of the IHS color transform to the processing of multisensor data and image enhancement. Proceedings International Symposium Remote sensing of arid and semi-arid lands; Cairo: 599-616.

Holopainen, M. 1998. Forest habitat classification by CASI airborne measurements. Forest and Landscape Research. in press.

Holopainen, M.; Wang, G. 1998. Accuracy of digitized aerial photographs for assessing forest habitats at plot level. Scandinavian Journal of Forest Research. 13(4): 500-509.

Hyppänen, H.; Pasanen, K.; Saramäki. J. 1996. Päätehakkuiden kuviorajojen päivitystarkkuus. Folia Forestalia. (in Finnish).

Häme, T. 1984. Landsat-aided forest site type mapping. Photogrammetric Engineering and Remote Sensing. 50: 1175-1183.

Häme, T. 1991. Spectral interpretation of changes in forest using satellite scanner images. Acta Forestalia Fennica 222. 111 p. ISBN 951-651-092-2.

Inkinen, M. 1997. Numeerisen ilmavalokuvan ja profiloivan tutkan soveltuvuus puustotunnusten kuvioittaiseen arviointiin. The applicability of digital aerial photographs and radar-derived stand profiles to the estimation of stand-wise characteristics. Helsinki University of Technology. 74 p. M.S. thesis (in Finnish with English summary).

Jaakkola, S.; Hagner, O. 1988. Multi-sensor remote sensing for forest monitoring. Proceedings of the IUFRO Subject Group 4.02.05. Meeting in Finland; 1988 August 29- September 2; Helsinki, Finland. Helsinki, Finland: University of Helsinki, Department of Forest Mensuration and Management, Research Notes 21: 146-157.

Jupp, D.L.; Strahler, A.H.; Woodcock, C.E. 1988. Autocorrelation and regularization in digital images I: Basic theory. IEEE Transactions on Geo-science and Remote Sensing. 26: 463-473.

Jupp, D.L.; Strahler, A.H.; Woodcock, C.E. 1989. Autocorrelation and regularization in digital images II: Simple image models. IEEE Transactions on Geoscience and Remote Sensing. 27: 247-258.

Liuha, P. 1996. Image fusion, combining spectral and textural features for improving image analysis. Department of Physics, University of Jyväskylä. (in Finnish with English abstract). 116 p.

Poso, S.; Häme, T.; Paananen, R. 1984. A method of estimating the stand characteristics of a forest compartment using satellite imagery. Silva Fennica. 18: 261-292.

Poso, S.; Paananen, R.; Similä, M. 1987. Forest inventory by compartments using satellite imagery. Silva Fennica. 21: 69-94.

Poso, S.; Karlsson, M.; Pekkonen, T.; Härmä, P. 1990. A system for combining data from remote sensing, maps, and field measurements for forest planning purposes. Helsinki, Finland: University of Helsinki, Department of Forest Mensuration and Management. Research Notes 23.

Pradines, D. 1986. Improving SPOT images size and multispectral resolution. SPIE Vol. 660, Earth Remote Sensing Using the Landsat TM and SPOT Sensor Systems.

Price, J.C. 1987. Combining panchromatic and multispectral imagery from dual resolution satellite instruments. Remote Sensing of Environment. 21: 119-128.

Ripple, W.J.; Wand, S.; Isaacson, D.L.; Paine, D.P. 1991. A preliminary comparison of Landsat Thematic Mapper and SPOT-1 HRV multispectral data for estimating coniferous forest volume. International Journal of Remote Sensing. 12: 1971-1977.

Sader, S.A.; Waide, R.; Lawrence, W.T.; Joyce, A.T. 1989. Tropical forest biomass and successional age class relationships to a vegetation index derived from Landsat TM data. Remote Sensing of Environment. 28: 143-156.

Varjo, J. 1993. Controlling continuously updated forest data by satellite remote sensing. Thesis for licentiate degree in forest management planning, University of Joensuu. 66 p.

Waite, M-L. 1993. Documentation of the SMI/92 forest management planning system. Helsinki, Finland: University of Helsinki, Department of Forest Resource Management.

Wang, G. 1996. An expert system for forest resource inventory and monitoring in the frame of multi-source data. Helsinki, Finland: University of Helsinki, Department of Forest Resource Management. Publications 10. 173 p. Ph.D. dissertation. ISBN 951-45-7289-0.

Wang, G.; Waite, M-L.; Poso, S. 1997. SMI user's guide for forest inventory and monitoring. Helsinki, Finland: University of Helsinki. Department of Forest Resource Management. Publications 16. 336 p. ISBN 951-45-7841-4.