ity. The interval HK2B3 shows a remarkable peak in X_{lf}, suggesting restricted/reducing conditions and decrease in pedogenesis, indicative of cold conditions during Early Pleistocene.

Thus a large gradient of pedogenic changes has been noticed in the studied section, that appears to be useful for regional correlation and climatic aspects during Plio-Pleistocene. The new ratios (indices) of reduction, hydration, oxidation and humification based on selective rock magnetic and geochemical properties, need to be tested in deriving broad climatic inferences for basin-wide regional application. The present study of the Siwalik palaeosols suggests that pedogenic magnetic mineral transformation is governed by the production of canted antiferromagnetic minerals during Pliocene and ferrimagnetic minerals during Pleistocene.

1. Burbank, D. W., Beck, R. and Mulder, T., in *Tectonic Evolution of Asia* (eds Yin, A. and Harrison, T. M.), Cambridge University Press, 1996, pp. 149–188.
2. Thompson, R. and Oldfield, F., *Environmental Magnetism*, Allen and Unwin Publ, London, 1986, p. 220.
3. Opdyke, N. D. and Channel, J. E. T., *Int. Geophys. Ser.*, 1996, **64**, 250–276.
4. Johnson, G. D., *Geol. Runds, Bd.*, 1979, **66**, 192–215.
5. Barry, J. C., Johnson, N. M., Raza, S. M. and Jacobs, L. L., *Geology*, 1985, **13**, 637–640.
6. Gaur, R. and Chopra, S. R. K., *Nature*, 1984, **308**, 353–355.
7. Behrensmeyer, A. K., Wills, B. J. and Quade, J., *Palaeogeogr. Palaeoclimatol. Palaeoecol*, 1995, **115**, 37–60.
8. Retallack, G. J., *Mem. Geol. Soc. India*, 1990, **32**, 36–51.
9. Srivastava, J. P., Verma, S. N., Joshi, V. K., Verma, B. C. and Arora, R. K., *Geol. Surv. India, Spec. Publ.*, 1988, **11**, 233–241.
10. Nanda, A. C., Sati, D. C. and Mehra, G. S., *J. Himalayan Geol.*, 1991, **2/2**, 151–158.
11. Kumar, R., Ghosh, S. K. and Sangode, S. J., *Geol. Soc. Am. Bull., Spec. Pap.*, 1999, **328**, 239–255.
12. Sangode, S. J., Kumar, R. and Ghosh, S. K., *Mem. Geol. Soc. India*, 1999, **44**, 221–248.
13. Phadtare, N. R., Kumar, R. and Ghosh, S. K., *Spec. Publ. Himalayan Geol.*, 1994, **15**, 69–82.
14. Sangode, S. J., Kumar, R. and Ghosh, S. K., *J. Geol. Soc. India*, 1996, **47**, 683–704.
15. Johnson, G. D. *et al.*, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, 1982, **37**, 63–93.
16. Ranga Rao, A., Agarwal, R. P., Sharma, U. N., Bhalla, M. S. and Nanda, A. C., *J. Geol. Soc. India*, 1998, **31**, 361–385.
17. Mehta, Y. P., Thakur, A. K., Nand Lal, Shukla, B. and Tandon, S. K., *Curr. Sci.*, 1993, **64**, 519–521.
18. Retallack, G. J., *Geol. Soc. Am., Spec. Pap.*, 1988, **216**, 1–20.
19. Dearing, J. A., Dann, R. J. L., Lees, J. A., Loveland, P. J., Maher, B. A. and O'Grady, K., *Geophys. J. Int.*, 1996, **124**, 228–224.
20. Maher, B. A. and Thompson, R., *Quat. Res.*, 1992, **37**, 155–170.
21. Dunlop, D. J. and Ozdemir, O., *Rock Magnetism: Fundamentals and Frontiers*, Cambridge University Press, 1997, p. 573.
22. Chen, J., An, Z. S. and Head, J., *Quat. Res.*, 1999, **51**, 215–219.
23. Kampf, N. and Schwertmann, U., *Geoderma*, 1983, **29**, 27–39.
24. Tardy, Y. and Roquin, C., in *Weathering, Soils and Palaeosols* (eds Martini, I. P. and Chestworth, W.), Developments in Earth Surface Processes–2, Elsevier, 1992, pp. 407–443.
25. Schwertmann, U., *Soil Sci. Soc. Am. J.*, 1988, **52**, 288–291.
26. Dekkers, M. J. and Rochette, P. R., *J. Geophys. Res.*, 1992, **97**, 17291–17307.
27. Davis, J. C., *Statistics and Data Analysis in Geology*, John Wiley and Sons, 1986, pp. 502–515.
28. Lowrie, W., *Geophys. Res. Lett.*, 1990, **17**, 159–162.
29. Dekkers, M. J., *Geophys. J.*, 1989a, **97**, 323–340.
30. Dekkers, M. J., *Geophys. J.*, 1989b, **97**, 341–355.
31. Wells, M. A., Fitzpatrick, R. W., Gikes, R. J. and Dobson, J. *Geophys. J. Int.*, 1999, **138**, 571–580.

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Land cover assessment in Jammu & Kashmir using phenology as discriminant – An approach of wide swath satellite (IRS–WiFS)

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Climatic and seasonal variations guide the change in the internal features of vegetation and thus the vegetation mapping. A correlation between the vegetation units and the normalized difference vegetation index (NDVI) is established and the spatial distribution of phenology and seasonal distribution is deduced for mapping. High amount of spectral variability contributed by phenological phases made us generate a large number of clusters to distinguish features. The study has significance in the light of national development needs *vis-à-vis* advancement expected in the future indigenous and international remote sensing missions. The study suggests that multi-date data consider the variability and enables us to delineate the land use and land cover pattern of Jammu & Kashmir. The regional phyto-phenological classified map provides details on vegetation stratum. They can be an excellent source of data for understanding the land dynamic processes and human interventions in the region. The map derived can delineate finer, the biogeographical zones.

INDIA encompasses a variety of climate, ranging from tropical, subtropical, temperate to alpine. There are

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variations in the altitude and temperature. Forests are one of the most magnificent expressions of nature on the earth, and also for a country like India, they are an important renewable natural resource and benefits from them are immense, mainly timber and non-timber forest products. They have been an important source of subsistence, employment, revenue and raw material to various industries. Forests play an important role in issues related to greenhouse gases and climate change, which are strongly linked to the maintenance of ecological balance, biological diversity, environmental stability, soil and water conservation, etc.

Forests being one of the most important naturally renewable resources, are true indicators of the ecological set-up prevailing in any area; it is therefore essential to manage them scientifically, which would require up-to-date statistics of their extent and type, etc. The forest cover assessment in India is being carried out by the Forest Survey of India (FSI) through visual interpretation of satellite remote sensing techniques at 1 : 250,000 scale, biannually[1]. The assessment has not been able to present realistic details. The process of deforestation in Indian forested landscapes is very slow. The illegal removal of trees from the intact forests is slow and selective. The density classes provided by FSI are too generalized to depict these changes, nor are the details of forest types given. To map these patches appropriate scale mapping is required, irrespective of cost-effectiveness. The frequent mapping can be done using IRS WiFS data which provide better information. Processing of the data set is efficient and economical.

The remarkable developments in science and technology in recent years have opened up new vistas for the well-being of mankind. Technological advances in space and computer hardware/software with mapping and analytical functionality along with decreasing cost, are the notable achievements. New technologies like remote sensing, geographical information system, global information system and digital image processing coupled with the state-of-the-art computers have revolutionized the process of information gathering, processing and utilization, for effective natural resources management. These have emerged as the most efficient tools for monitoring and management of forest resources at global, regional and local scales.

In the present study a wide field sensor with the capability of covering a large area in a single instantaneous field of view (IFOV) has been used, which avoids illumination differences and has better temporal resolution. Such data sets have found considerable acceptance for land cover studies at regional level, demonstrated through NOAA-AVHRR data. However, many studies have found NOAA data deficient due to their 1.1 km resolution. IRS-WiFS data are the first of its kind to overcome the deficiencies experienced[2–5]. The study focuses on the potential of temporal IRS-1C WiFS data for monitoring the phenological fluxes of land cover pattern in Jammu & Kashmir (J&K) at a regional scale. The normalized difference vegetation index (NDVI) is evaluated for monitoring seasonal changes in vegetation. Attempts have been made to stratify land cover using the phenological variation as discriminant. Hybrid approach of classification has been used and it provided good results. The regional phyto-phenological classified map provides details on vegetation stratum. They can be an excellent source of data for understanding the land dynamic processes and human interventions in the region.

The state of J&K, located in the far north of the Indian Republic, is a mountainous area in the north-west Himalayas, that shares international boundaries with Pakistan in the west, China in the north and Tibet in the north-east. Punjab and Himachal Pradesh are its neighbouring states within the country. The three major territories, i.e. Jammu, Kashmir and Ladakh differ in terms of climate, physiography, ethics and culture. All the three regions experience different climatic patterns. Cold desert-like condition prevails in Ladakh, and alpine, temperate and subtropical type in the rest of the state. The four distinct seasons are Spring (March–May), Summer (June–August), Autumn (September–November) and Winter (December–February). The average maximum and minimum temperatures are 31°C and 18°C in July and 4°C and 2°C in January, except in Ladakh where maximum temperature is 30°C and minimum temperature is –50°C. Annual rainfall in the state varies from 100 to 155 mm, except in Ladakh where the precipitation is low and varies from 100 to 200 mm. Srinagar receives only about 700 mm of rain annually because of the influence of Pir Panjal range. The sub-tropical climate of Jammu is characteristic; very hot summer and monsoon rains during June–August. January is the coldest month of the year, though the temperature never touches 0°C. There is an abrupt rise in temperature during March and it reaches up to 44°C during June[6].

The study area presents a wide climatic spectrum and phenological variation. The region supports diverse vegetation types and species diversity. The recent years have seen excessive anthropogenic pressure on forest cover and its quality. Hence, regular monitoring of the forest cover and its type is essential to evolve forest management and conservation study.

WiFS sensor, having spectral bands B1 (0.62–0.68 μm) and B2 (0.77–0.86 μm) and a high temporal resolution, i.e. 5 days and large area coverage (810×810 km^2) has been used[7,8]. The details available in this data are best suited for land cover characterization at a regional scale. Suitability of such moderate-resolution data for regional vegetation compared to AVHRR data, should make better choice for monitoring/operation and research. The pixel size of 188 m suits regional scale mapping. The data sets were of 13 January 1998, 1 March 1998, 20 April 1998, 15 May 1998, 15 June 1998, 12 October 1998, 9 November 1998 and 4 December 1998 (Figure 1).

First-order atmospheric corrections were done by dark pixel subtraction technique. This technique assumes that there is a high probability that there are at least a few pixels within an image which should be black (0% reflectance). However, because of atmospheric scattering, the image system records a non-zero DN value at the supposedly dark-shadowed pixel location. This represents the DN value that must be subtracted from the particular spectral band to remove the first-order scattering component[9].

Images were registered geometrically using toposheets of Survey of India (SOI) on 1 : 1000 000 scale. The common uniformly distributed ground control points (GCPs) were marked and imagery was resampled by nearest neighbourhood method. All the data were then co-registered for further analysis. The rms error of 0.03 pixels was accepted during the process of geometric correction.

The NDVI is one of the ratios[10], which has been shown to be highly correlated with vegetation parameters such as green-leaf biomass and green-leaf area and hence is of considerable value for vegetation discrimination[11–17].

$$NDVI = (IR - R)/(IR + R).$$

Moreover, it reduces variation introduced by surface topography and compensation for variation in radiance as a function of sun elevation for different parts of scene, which is highly valuable in continental studies.

The maximum NDVI is calculated to determine the index of greenness of the vegetation at the time of peak growth season. It simply provides the maximum greenness of the vegetation in the study period.

$$NDVI_{max} = Max\ (NDVI_i \ldots NDVI_n).$$

For land cover mapping, layer-stacked image of maximum NDVI for all data sets and raw bands of October was taken. The mapping step involves the use of a clustering algorithm based on the *K*-means algorithm, run on monthly NDVI maximum value, NIR and Red of November composite. Each cluster was assigned a preliminary cover-type label, taking care of the spatial pattern and spectral or multi-temporal statistics of each class and on comparison with ancillary data and extensive ground truth. Ancillary data included descriptive land cover information, NDVI profiles and class relationships to the other land cover legends. Related 'single category' classes were then grouped using a convergence of evidence approach[9]. The snow and cloud classes were masked out. Some of the shadow areas were put to the respective classes on the basis of extensive field knowledge. The unsupervised classification was followed by post-classification refinement for the coherent set of classes. On the final output median filter was carried out for image smoothening (Figure 2).

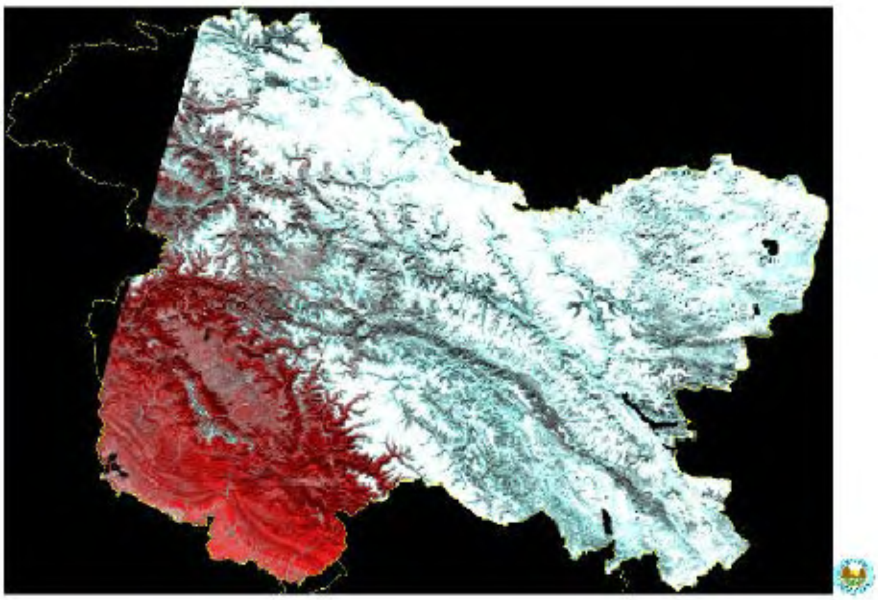

Figure 1. False colour composite of Jammu & Kashmir IRS–1C/1D WiFS data.

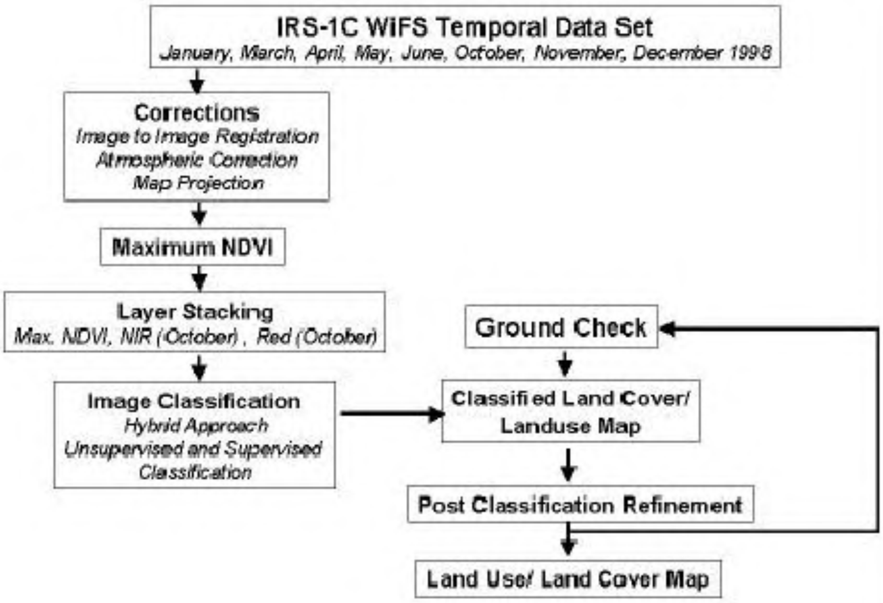

Figure 2. Approach for land cover assessment in Jammu & Kashmir using wide swath satellite.

Accurate quantitative information on the distribution and phenology of vegetation formation is extremely limited and yet is fundamental for the effective management of forest resources. Eight different time-period NDVI images have shown a representativeness for seasonal changes. The values of NDVI are from – 0.367 to 0.366 (January), – 0.353 to 0.507 (March), – 0.381 to 0.402 (April), – 0.411 to 0.546 (May), – 0.324 to 0.541 (June), – 0.449 to 0.544 (October), – 0.369 to 0.504 (November) and – 0.440 to 0.453 (December). The maximum NDVI image has been computed to represent the maximum foliage cover in the study period.

To demonstrate the utility of WiFS data for monitoring vegetation status at a regional scale, selected temporal plots were selected and analysed for the study area. NDVI values obtained for different cover types are plotted in Figure 3. The representative sites selected for each cover type indicate the internal variation of the NDVI response of the cover type. For each location area, sample NDVI and averaged NDVI values were plotted for the composite time period. The NDVI images were analysed for the foliage cover in the respective time period. The maximum NDVI image is a true indicator of foliage cover irrespective of the areas, which are accounted forest legally, but bear less or no foliage. The maximum NDVI image was computed for the maximum foliage cover or greenness in the study period for each forest class. In the coniferous locations, NDVI values showed a uniform trend and an increasing trend in October. The temperate forest had a slight peak during May, with a steep decline in values from June to December (data for August and September were not available owing to heavy cloud cover). Sub-alpine forest had moderate NDVI values, with slight peak during October. Dry deciduous types had high photosynthetic activity, with the highest during October. The non-forest class, viz. alpine meadows/scrub shows almost similar pattern of NDVI values as sub-alpine region throughout the year. Agriculture shows uniform NDVI values during the study period, with a high value in May. The comparative NDVI values of the valley agriculture are less, but follow uniform trends, with unexpected decline in October, perhaps due to cloud/snow cover. Orchards showed the bimodal curves in March and October. From the preliminary analyses, it is apparent that different cover types exhibit characteristic NDVI curves. The trends of greenness for the individual classes are distinguished and are useful to identify the forest types. In spite of high cloud/snow cover, the NDVI values confirm the trend of temporal variation, i.e. phenology. Intensive data set may help in tracing the seasonability, to establish the timing of ‘green-up’ and ‘senescence’ and estimate the length of the growing season, year by year. Monitoring of the crop development throughout the growing period is possible for the agricultural areas.

The geographical area of J&K is 222,235 km^2. According to the State Forest Report, 1999, of FSI, the recorded forest area in the state occupies only 20,441 km^2, i.e. 9.2% of its area. The analysed area in the present study is about 204,571.84 km^2, as the data set for the area adjacent to Pakistan could not be procured for cloud/snow-free months. The available months were totally cloud/snow covered and could not be used for land cover estimation. The forest cover estimated in the present study is worked out to be 14% of

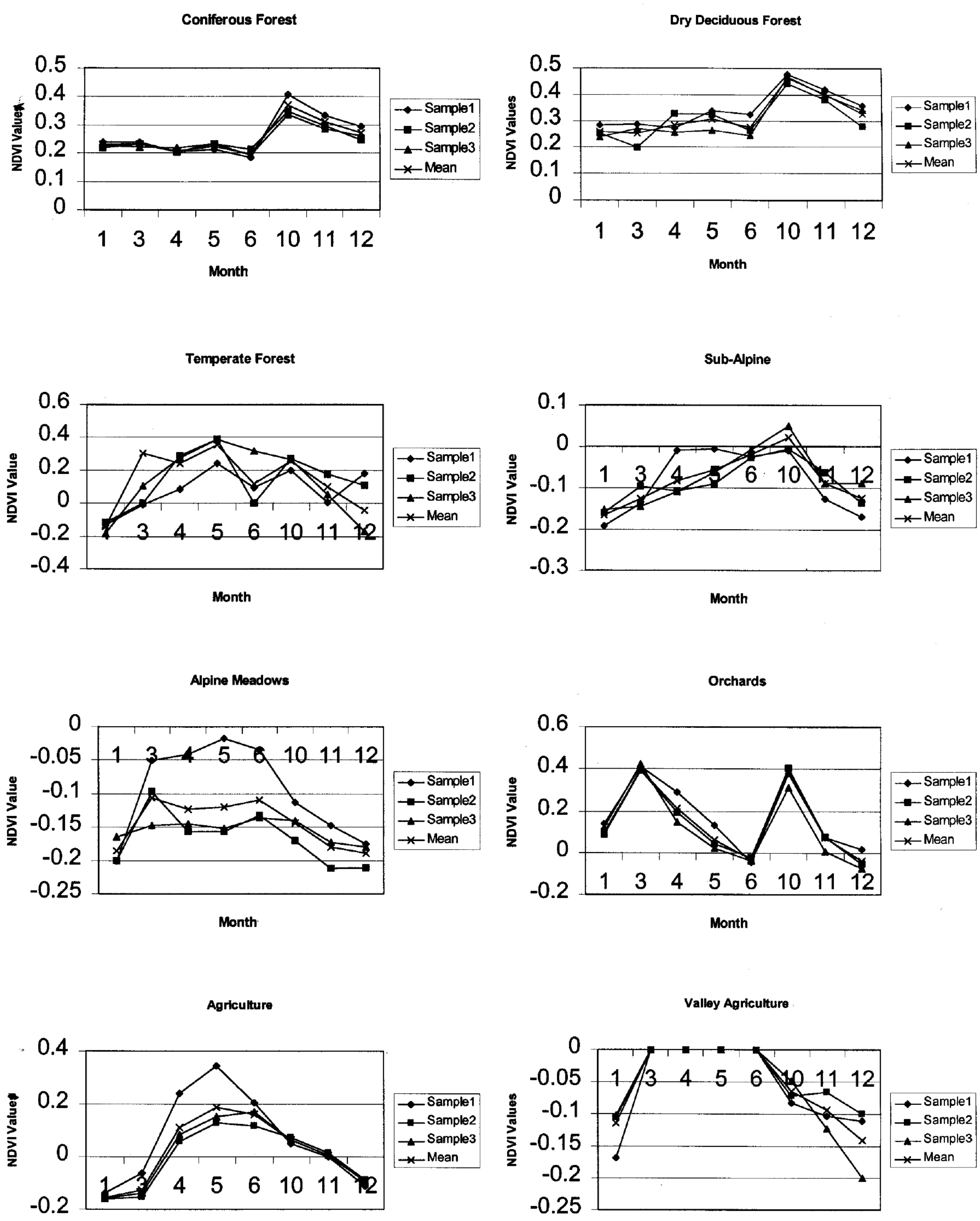

Figure 3. NDVI curves for the different classes.

the studied geographical area. Perhaps, the limited data sets used by FSI, viz. November–December 1996 and September–October 1997 are attributed to underestimation of high altitude forest cover (Figure 4)[1].

Kashmir is characterized by coniferous (chir, pine), Himalayan temperate (broad-leaved), sub-alpine and tropical dry deciduous forests (Table 1).

The healthy vegetation in the Himalayan temperate forest is in the beds and banks of streams and canals. In the Pir Panjal region, the forest occurs between 2000 and 3200 m. The forest can be further classified as 'moist temperate' or 'dry temperate' types, but the present study has limitations to discriminate it because of coarse resolution, which is unable to trace ground

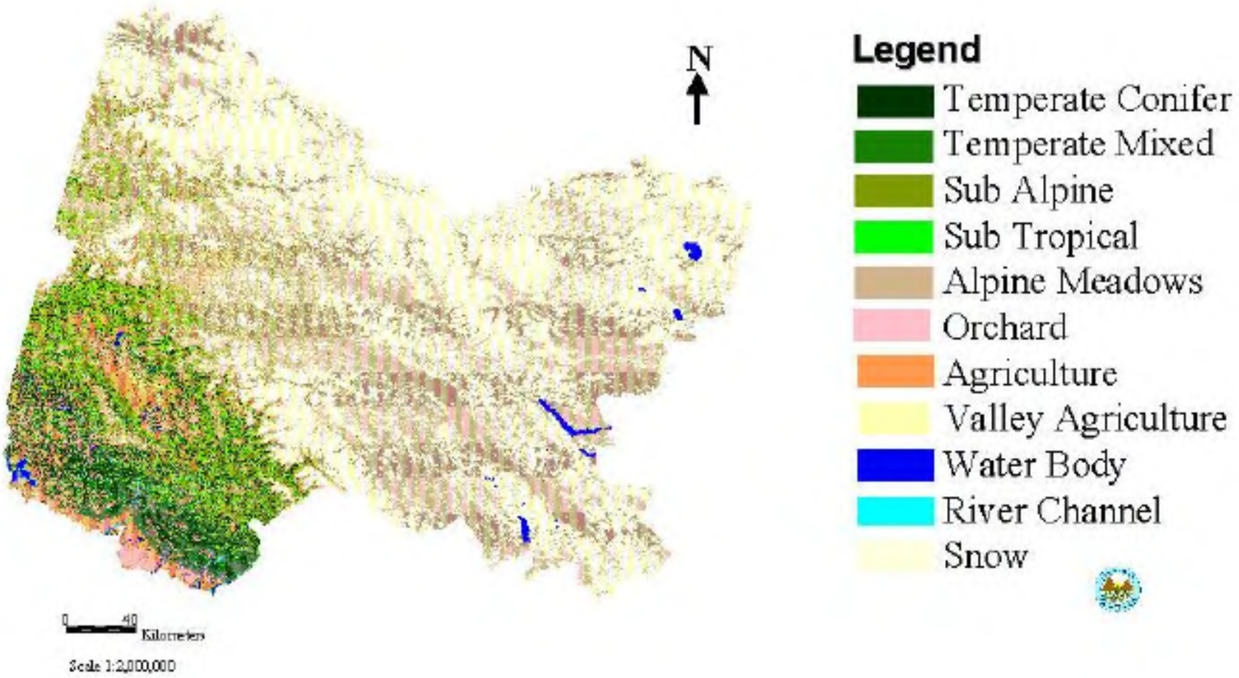

Figure 4. Land cover map of Jammu & Kashmir prepared using temporal IRS–1C WiFS data.

Table 1. Forest cover/types mapped *vis-à-vis* Champion and Seth[25]

Cover types (Mapped in present study)	Forest types (Champion and Seth)
Himalayan temperate forest	Himalayan moist temperate forest
	Himalayan dry temperate forest
Coniferous forest	Sub-tropical pine forest
	Sub-tropical dry evergreen forest
Sub-alpine forest	Sub-alpine forest
Tropical dry deciduous forest	Tropical dry deciduous forest
Alpine scrub/meadows	Moist alpine scrub
	Dry alpine scrub

configuration. The pine zones extend from 1600 to 3000 m; specially *Pinus wallichiana* is found at 2800 m and is replaced by *Abies pindrow* at 2500 m. The deodar resides at an altitude of 1800–2600 m.

The sub-alpine forest constitutes Rhododendron and Juniper, with some shrubs of Betula/Abies. The low linings are with blue pine forest (*P. wallichiana*) and deciduous scrub.

The dry and mixed deciduous type continues the vegetation of the Punjab plains. The forest belt comprises Acacia, Bauhibia variegate–Oogeinia, Lanneas, coromandelical – hymenodictyon oexcelsum, Dodonaea scrub, mixed semi-deciduous and subtropical pine (*P. roxburghii* 'chir') forest.

Excessive encroachment (cultivation and colonization) has reduced the forest to few relict packets. The major forest produce is timber and fuelwood. Due to excessive biotic pressure, heavy exploitation for timber, fuelwood extraction, grazing and other local uses, the forest cover has been reduced and many areas have been degraded. Efforts are underway to restore and rehabilitate degraded areas by bringing them under massive afforestation, social forestry and fuelwood/fodder development programmes.

Non-forest areas like alpine meadows/scrub are almost a treeless expanse. Due to scarcity of the precipitation available, the plants are generally found growing along moist river margins or in moist rock crevices. The alpine herbs grow in belts along the edges of melting glaciers and never spread to exposed slopes. The characteristic features of the vegetation are the cushion-like habit of plants, which is an adaptation for cold, dry winds and blizzards[18].

About 60% of the population is engaged in valley agriculture/agriculture, directly or indirectly. Major crops are paddy, wheat and maize with barley, sorghum and gram as minor ones. Due to the increasing demand and complex agricultural problems of the temperate and cold, arid region, the state has been forced to import a large amount of food grains from other states.

Cultivation of fruits and other horticulture crops has been practised in J&K over the ages. The agroclimatic conditions are well-suited for cultivation of a large number of temperate and sub-tropical fruits of different varieties, viz. mango, banana, orange, apple, cherries, pear, mulberry and apricot.

The three rivers, viz. the Tawi on which Jammu city stands, the Chenab and the Jhelum together with its tributaries, water the fertile valley of Kashmir. The major water bodies are Dal and Nagin. The lakes abound swampy lagoons and distinctive hydrophytic formations.

The higher ridges and upper reaches of the state are permanently snow-covered, i.e. glaciers. The foothills and high passes get covered with the seasonal snowfall. Some of the regions have low-lying clouds.

The temporal data provide a wider view to trace out the qualitative as well as quantitative status of the vegetation. NOAA has been widely used the worldover for mapping at global and continental levels for green coverage, productivity, early warning and environmental monitoring, in spite of coarser spatial resolution[19–22]. The introduction of WiFS offered an advantage of competitive spatial, spectral and temporal resolution for vegetation studies. The application of WiFS for regional studies has been established by earlier workers[2,3,7,8]. For a region like J&K, WiFS has been found useful with its ability to present temporal data set to overcome the cloud and snow cover problem to some extent. Although the WiFS data provide a novel means to qualify and quantify land use/cover, one must be aware of their limitations. The wider pixels may create complexity in interpretation of the components. Over-estimation or underestimation of the vegetation cover may occur, resulting in varied accuracy and variable nomenclature/classes for the same core project needs[23,24]. The climatic and atmospheric parameters play an important role in these regional data sets and therefore often have an undesirable mixture of potential versus actual land cover features. It is also clear that the atmospheric effects, although minimized by the different algorithms, will have an impact on computation of NDVI images and utmost care is required for areas subjected to strong atmospheric haze. This paper has emphasized exclusively, the role of medium-resolution sensor for vegetation monitoring. It can be further exploited in conjunction with high-resolution sensors and extensive ground truth to provide for quantitative forest resource information. The integrated values, are a quantitative measure for defining the similarities and differences between the NDVI characteristics of the major vegetation formations. It can be further correlated with the seasonal net productivity. NDVI can also be evaluated for monitoring seasonal changes in vegetation.

In the present study, actual forest cover area has been estimated as 14% of the studied area of J&K, while FSI has reported the cover estimate as 9.2% of total geographical area of the state. The analysed area in the present study is about 204,571.84 km^2, as the data set for the area adjacent to Pakistan cannot be procured for cloud/snow-free months. The available months were totally cloud/snow covered. These were not useful for land cover estimation. Perhaps the limited data sets used by FSI, viz. November–December 1996 and September–October 1997 are attributed to underestimation of high-altitude forest cover. The regional phytophenological classified map provides details on vegetation stratum. They can be an excellent source of data for understanding the land dynamic processes and human interventions in the region. Hybrid approach of classification has provided good results.

Observation of forests by satellites provides the best hope of assessing the current state of forests, monitoring the changes over exhaustive areas and understanding the complex processes involved. This helps policy makers to assess the current situation, judge long-term trends and help to manage forest resources sustainably. In this context, IRS 1C/1D WiFS has emerged as the most optimal means for monitoring and management of forest resources on a regional scale. The repetitive coverage provided by the sensor helps in selecting the required season/period data for phenological state of vegetation, phytogeographical region, land use practice with the best illumination and IFOV. Each pixel of the data provides a wide range of ground information and conditions, which may give rise to complexity in interpretation of the components at pixel-level. Phenology has become an important component for categorizing the forest types. WiFS is ideally suited to build phenological trends. These trends are useful to identify the forest type. NOAA-AVHRR is good for global and continental studies, but for regional level assessment it does not provide detailed information because of its low resolution. LISS III cannot be compared because of large volume of data and low temporal resolution. Its amenability to DIP and WiFS can be utilized efficiently and economically to generate forest information annually and to monitor large deforestation patches. The present study supports the use of WiFS data for land cover and land use mapping at meso-scale for regional level assessment and monitoring. The advantage of a sensor lies in suitable spatial and spectral resolution for regional level, competitive band combination for vegetation studies and temporal resolution for vegetation dynamics. It offers wider coverage for comparison of regional or continental level studies. Its effectiveness is in discrimination of forest types and major crops and other land cover and uses. The accuracy of medium-resolution WiFS data for land cover classification is comparable to medium-resolution data in regions dominant with uniform features. Hybrid approach of classification proved to be more useful than other approaches. WiFS data have been found to be satisfactorily for forest assessment, mapping and delineation.

1. Anon. The State of Forest Report, Forest Survey of India, New Delhi, 1999.
2. Singh, Sarnam, Agarwal, Shefali, Joshi, P. K. and Roy, P. S., in Joint Workshop of ISPRS Working Groups I/1, I/3 and IV/4: Sensors and Mapping from Space, Hanover, Germany, 27–30 Septemer 1999, 1999a.

3. Singh, Sarnam, Agarwal, Shefali, Joshi, P. K. and Roy, P. S., in XIX INCA International Congress, Vasco-Da-Gama, Goa, 26–28 October 1999, 1999b.
4. Roy, P. S. and Joshi, P. K., *Int. J. Remote Sensing* (communicated).
5. Joshi, P. K., Singh, Sarnam, Agarwal, Shefali and Roy, P. S., *Curr. Sci.*, 2001, **80**, 941–947.
6. Anon, *Biodiveristy of Jammu and Kashmir*, World Wide Fund for Nature, New Delhi, 1997.
7. Potdar, M. B., *J. Indian Soc. Remote Sensing*, 1990, **18**, 1–7.
8. Ray, S. S., Pokharana, S. S. and Ajai, *Int. J. Remote Sensing*, 1994, **15**, 1085–1090.
9. Lillesand, Thomas M. and Kiefer, Ralph W., in *Remote Sensing and Image Interpretation*, John Wiley & Sons, Inc., New York, 1999.
10. Rouse, J. W., Haas, R. H., Schell, J. A. and Deering, D. W., in Proceedings 3rd ERTS Symposium, 1973, vol. 1, pp. 48–62.
11. Curran, P. J. and Franquin, P., *Prog. Phys. Geogr.*, 1980, **4**, 315.
12. Holben, B. N. and Frasher, R. S., *Int. J. Remote Sensing*, 1984, **5**, 145.
13. Tucker, C. J., Holben, B. N., Elgin, J. H., Jr. and McMurtrey, J. E., *Remote Sensing Environ.*, 1981, **11**, 171.
14. Hatfield, J. L., *Remote Sensing Environ.*, 1983, **13**, 301.
15. Jackson, R. D., Slater, P. N. and Pinter, P. J., *Remote Sensing Environ.*, 1983, **15**, 187.
16. Justice, C. O., Townshend, J. R. D., Holben, B. N. and Tucker, C. J., *Int. J. Remote Sensing*, 1985, **6**, 1271–1381.
17. Roy, P. S., in *Environmental Studies in India* (ed. Balakrishnan, M.), Oxford and IBH, New Delhi, 1993, pp. 335–363.
18. Fung, I. Y., Tucker, C. J. and Prentice, K. C., *J. Geophys. Res.*, 1987, **92**, 2999–3015.
19. Kashyap, S., *J. Indian Bot. Soc.*, 1925 **4**, 327–334.
20. Townshend, J. R. G., in Report No. 20, International Geosphere Biosphere Programme, Stockholm, 1992.
21. Benedetti, R., Rossini, P. and Taddei, R., *Int. J. Remote Sensing*, 1994, **15**, 583–596.
22. DeFries, R. S. and Townshend, J. R. C., *Int. J. Remote Sensing*, 1994, **15**, 3567–3586.
23. Belward, Alan S., Estes, John E. and Kline, Karen D., *Photogramm. Eng. Remote Sensing*, 1999, **65**, 1013–1020.
24. Loveland, Thomas R., Zu, Shillang, Ohlen, Dionald O., Brown, Jessyin F., Reed, Bradlat C. and Yang, Liming, *Photogramm. Eng. Remote Sensing*, 1999, **65**, 1021–1032.
25. Champion, H. G. and Seth, S. K., in *A Revised Survey of Forest Types of India*, New Delhi Govt. Publication, 1968.

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The 1908 Tunguska catastrophe: An alternative explanation

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More than seventeen reasons are presented as to why the fiery Siberian event of 30 June 1908, near the Stony Tunguska river, was not caused by the infall of a stony asteroid, nor of an (icy) comet, but rather by the volcanic ejection of some 10 Mt of natural gas. For the volcanic (outflow) interpretation, estimates are presented of the involved mass and kinetic energy of the vented natural gas, its outflow timescale, supersonic and subsonic ranges, and buoyant escape towards the exosphere. The Tunguska event may well have been the present-day formation of a kimberlite.

ON 30 June 1908, a quarter past 7 a.m. [corresponding to 0^h $(13.6 \pm 5)^m$UT], hell broke loose in the Tunguska area, more than 700 km north-northwest from lake Baikal, with an epicentre at (101°53′40″E, 60°53′09″N). The ground trembled, Barisal guns were heard firing (also called 'brontides'[1]), whirlwinds or gusts blew, and the sky was torn by columns of fire. Trees were felled in an on-average radial pattern, over an area of 2150 km^2, and scorched in patches over a central area adding up to one fifth that size. Hunters and herdsmen, tepees, storage huts and dozens (hundreds?) of reindeer were blown into the air and/or incinerated in various places of that area. Even at Vanavara, the nearest trading post (at a distance of 65 km from the epicentre), people felt burning heat in their faces and were thrown off their feet[2–6] (Figure 1).

The Tunguska epicentre coincides with the middle of the 250 Myr-old 'Kulikovskii' volcanic crater which forms part of the Khushminskii tectono-volcanic complex; several tectonic faults pass through this region[7]. Eyewitnesses (Evenks) have reported that during that very morning, dozens of new, funnel-shaped 'holes' were formed of diameters 50 m, as well as a 'huge dry ditch' ('tear in the ground', 'dry stream', probably 1 km long). The first expedition into the area, in 1910, was carried out by a wealthy Russian merchant and goldsmith named Suzdalev, who, on return, urged the local inhabitants to keep silent about it. Had he discovered diamonds?

The present-day swamps near the epicentre had supposedly been flat forest areas and/or natural peat bogs before, also (at least) one of the hillocks[2]. The earliest scientific expeditions, organized by Leonid Kulik, some 20 years later, found most of those holes filled with water. They spoke of the near-environment (5 km) of the epicentre as the 'cauldron', or 'amphitheatre', containing the 'Merrill circus', according to their topography and treefall pattern. Lake Cheko, some 8 km to the

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