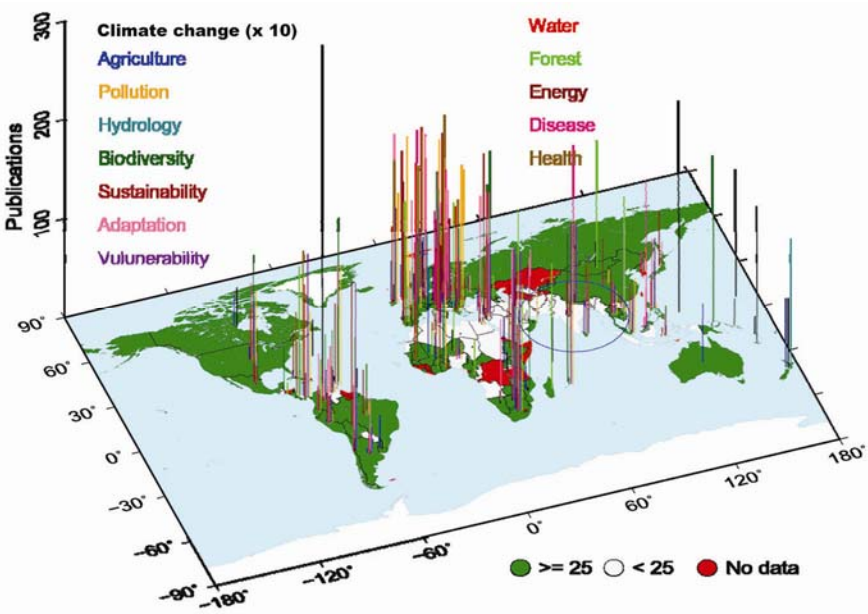

Figure 2. White-space mapping: country-wise distribution and number of *SCI* publications in climate change as a function of GDP. Countries with 25 or more publications per 100 billion USD are shaded with green and others are shown in white (source: *Web of Knowledge*).

implications of such a presence in the international techno-policy forums are obvious. It is likely that, recognizing the obvious advantages of such a presence, a conscious effort has been made by the Chinese policy-makers. It is worth noting that India appears to be essentially white, with less than 25 publications per 100 billion USD, while most of the countries, except for a few in Africa, are shaded green, indicating more than 25 publications per 100 billion USD (Figure 2).

It is clear that India with its climatic diversity and vulnerability to climate change[4–6] needs to put urgent efforts to create a meaningful knowledge presence to support its policy. It is encouraging that significant and long-term efforts are being planned by the Ministry of Earth Sciences, Government of India, in the form of its Climate Research Centre, Monsoon Mission, etc. Similarly, the Council of Scientific and Industrial Research (CSIR) and the Department of Science and Technology continue to support basic and applied research in earth sciences. The Indian Council of Agricultural Research also has a significant effort allocation for climate change. However, many of these initiatives may have to divide efforts in application, outreach and science; thus the contribution of programmes to the filling up of the white space in research remains to be seen.

More importantly, however, concerted and well-planned efforts are needed to enhance cross-sectoral research to quantify and assess impact of climate change through integrated approach. A notable effort in this direction is the 11th Five Year Plan project of CSIR on Integrated Analysis for Impact Mitigation and Sustainability (IAIMS), a network initiative among a number of institutions and academia to develop a multidisciplinary platform in climate change research. It is also encouraging to note that the Planning Commission of India, in March 2012, had recommended the formation of an inter-agency network for cross-sectoral research and outreach in sustainability and climate adaptation (Network Initiative on Sustainability, Climate Adaptation and Mitigation: NISCAM). Such a sustained inter-agency network will go a long way to colour the research space of India in climate research.

1. Katzela and Naghshineh, M., *IEEE Pers. Commun*., 1996, **3**, 10–31.
2. Guo, X., Roy, S. and Conner, W. S., In Proceedings of the IEEE VTC'03-Fall, Florida, USA, 2003, pp. 1437–1442.
3. Zhao, Q. and Sadler, B. M., In *IEEE Signal Processing Mag.*, 2007, **24**, 79–89.
4. Ramesh, K. V. and Goswami, P., *Geophys. Res. Lett*., 2007, **34**, L23704.
5. Goswami, P. and Ramesh, K. V., *Curr. Sci.*, 2008, **94**, 476–480.
6. Naidu, C. V. *et al.*, *J. Geophys. Res. Atoms.*, 2009, **114**, D24108.

ACKNOWLEDGEMENT. This work was supported by the CSIR Network Project IAIMS, India.

Received 10 August 2012; revised accepted 22 March 2013

K. V. RAMESH
P. GOSWAMI*

Climate and Environmental Modelling Programme,
CSIR Centre for Mathematical Modelling and Computer Simulation,
Wind Tunnel Road,
Bangalore 560 037, India
**For correspondence.*
e-mail: goswami@cmmacs.ernet.in

Identification of invasive plant species using field spectro-radiometer and simulated Hyperion spectra – a rapid mapping of invasiveness

'Invasiveness is establishment of self-sustaining plant populations that are expanding within a natural plant community with which they had not previously been associated.'[1] Invasive species are described as a 'catastrophic wildfire in slow motion' as they cross geographic boundaries, spanning landscapes, land ownerships and jurisdictions[2]. Presence of invasive plant species alters the structure and function of terrestrial ecosystems by changing the species composition and resource availability[3,4]. These ecological effects frequently impact population dynamics and impose selective pressure on native species and hence influence evolutionary trajectories of the natural community[5,6].

Like other regions around the globe, several parts of India have been invaded by different plant species like *Lantana*, *Eupatorium*, *Cannabis*, *Parthenium*, etc. The Himalayan foothills are the most active zone of human interaction with the natural resources, which has resulted into widespread distribution of these invasive species[7]. This area has drawn attention of ecologists, environmentalists and other researchers for its rapidly changing land use/land cover, habitat fragmentation and biodiversity patterns and now due to colonization of *Lantana*, *Eupatorium*, *Cannabis* and *Parthenium*. The Himalayan landscape being the abode of natural and protected forests and having acute impact on the downstream landscape, needs special attention for management strategies.

For proper forest management we need accurate information on spatial location and the spread of the invasive species. Mapping of these species using remotely sensed observations is efficient and cost-effective in comparison to field-based measurements[8]. Researchers have used both broadband multi-spectral and narrow-band hyperspectral sensors for the purpose of mapping[9,10]. It has been found that on many occasions, invasive species are likely to occur below the tree canopy or may exist as mixed vegetation[11]. This makes it difficult for optical space-borne sensors to detect the invasive species. Abundance maps produced by spectral unmixing from hyperspectral sensors can be a promising answer to this constraint. However, this technology is expensive and demands high degree of preprocessing[12]. Before carrying out airborne or space-borne hyperspectral imaging survey, it is advisable to carry out field measurements using hand-held field spectro-radiometer to find out the possibilities for mapping plant invasion with this technology[13]. The present study was undertaken for a rapid identification of invasive plant species using field spectro-radiometer in Shiwalik Himalaya.

Analytical spectral device (ASD) spectro-radiometer (FieldSpec 2) ranging between 350 and 1050 nm was used to collect spectral signatures of different invasive species[14]. The collection of spectral signatures serves the purpose of reference spectra while applying various mapping algorithms on remotely sensed hyperspectral images. To carry out the experiment, field plots were selected in the Motharawala block of Rajaji National Park. The fieldwork was carried out on 6 April 2012. The field spectrum can vary with sample site location, time of collection and background. Therefore, reflectance of fresh leaf samples of four different plant species (*Lantana*, *Parthenium*, *Eupatorium* and *Cannabis*) was collected under clear sky condition, in nadir direction between 10 a.m. and 2 p.m. in a small geographical extent with no background soil. The target invasive species were at different phenological stages but in the same season at the time of field survey. Calibration was done before every measurement, using dark current optimization and white reference (Spectralon panel). Minimum of five spectra were collected for each species and averaged to create a single spectrum for each species. Attempt was also made to simulate spectra similar to space-borne Earth Observation (EO) 1 Hyperion sensor in terms of wavelength and full width at half maximum (FWHM). For this, a reference Hyperion image (captured on 9 March 2012) of the study area was used. All the generated field spectra were spectrally resampled with reference to the Hyperion bands with a Gaussian model with FWHM spacing (identical to Hyperion bands).

The first derivative (1st D) spectrum represents the change in absolute reflectance with wavelength. Spectral derivatives are often found useful for various

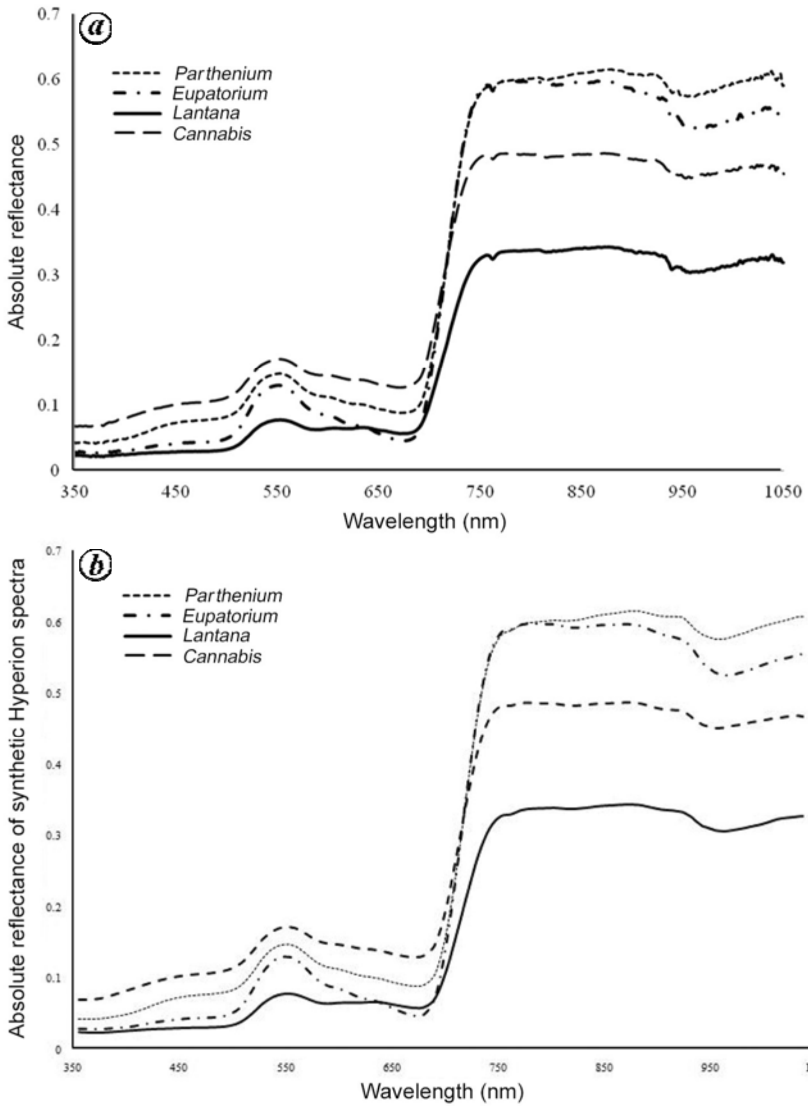

Figure 1. Original spectra captured using hand held spectro-radiometer. ***b***, Synthetic Hyperion spectra of the target species.

applications as the effect of solar illumination, terrain and soil background is minimized after differentiation. Derivatives are also useful in finding the position of red edge, other reflectance peaks and absorption minima[15]. Also derivatives remove the effect of constant background spectra. First-order numerical differentiation using three-point Lagrangian interpolation was performed on both field spectra and synthetic Hyperion spectra. Spectral angle is also a good measure to quantify the (dis)similarity between the spectra. Spectral angle mapper (SAM) is an automated method for (dis)similarity measurement and has been incorporated in various standard image processing systems. In SAM analysis, each spectra (S) is considered as a vector in a space with dimensionality equal to the number of spectral bands[16]. For any sensor with n number of bands, the spectral angle (θ) between two spectra (S_1 and S_2) can be measured using the following formula

$$\theta = \cos^{-1}\left(\frac{\sum_{i=1}^{n} S_{1i}S_{2i}}{\sum_{i=1}^{n}(S_{1i}^2)^{1/2}\sum_{i=1}^{n}(S_{2i}^2)^{1/2}}\right). \quad (1)$$

The θ value varies from 0 (completely different spectra) to 1 (completely similar spectra). SAM analysis was performed on field-collected absolute reflectance (AR) and its 1st D with *Lantana* as reference spectra.

The original and synthetic Hyperion spectra of the target species (*Lantana*, *Parthenium*, *Eupatorium* and *Cannabis*) are shown in Figure 1. The original spectra are collected at an interval of 1 nm showing detailed variation of the response pattern. These spectra provide distinct response pattern between 450 and 600 nm and beyond 800 nm. The difference in absolute reflectance in the 450 and 600 nm wavelength interval is less than that of the 800 nm wavelength. However, differentiation between *Parthenium* and *Eupatorium* is relatively difficult at higher wavelength regions. The synthetic spectra show relatively less variation due to larger wavelength (10 nm) sampling interval. For all the target species, the spectra in Figure 1 *b* show similar pattern. Most of the multispectral satellite sensors dwell in the larger wavelength (~ 100 nm) sampling interval. Hence they are unable to pick these distinct zones to differentiate among the species.

First derivative of the original and synthetic spectra of the target species (*Lantana*, *Parthenium*, *Eupatorium* and *Cannabis*) is shown in Figure 2. The 1st D represents absolute changes in the reflectance and minimizes the impacts of several environmental noise factors. As a result, reflectance pattern is enhanced at particular wavelengths which helps in differentiating among the features. The 1st D of the original spectra represents 525 and 720 nm as distinct wavelengths to differentiate among the target species. However, the 1st D of synthetic Hyperion spectra provides four distinct wavelengths – 525, 570, 710 and 930 nm for species differentiation.

Results of SAM analysis are shown in Table 1. Using AR, the minimum spectral angle distance between *Lantana* and other species was as follows: *Parthenium* 15.635°; *Eupatorium* 18.738°; *Cannabis* 27.127°. Using 1st D, the minimum spectral angle increased to 44.928° with *Parthenium*. Use of 1st D in this case certainly facilitates in differentiating *Lantana* from other invasive species. Using synthetic Hyperion spectra (SynH), the minimum spectral angle distance between *Lantana* and other species was: 14.76° for *Parthenium*; 16.863° for *Eupatorium* and 24.632° for *Cannabis*. Using 1st D SynH, the minimum spectral angle increased to 25.71° with *Parthenium*. Hence processing of SAM method using 1st D provides better differentiation among the plant species.

This work aims at demonstrating the capabilities of hyperspectral remote sensing techniques for identifying invasive plant species and differentiating among them. A hand-held spectro-radiometer was used to capture real-time spectral

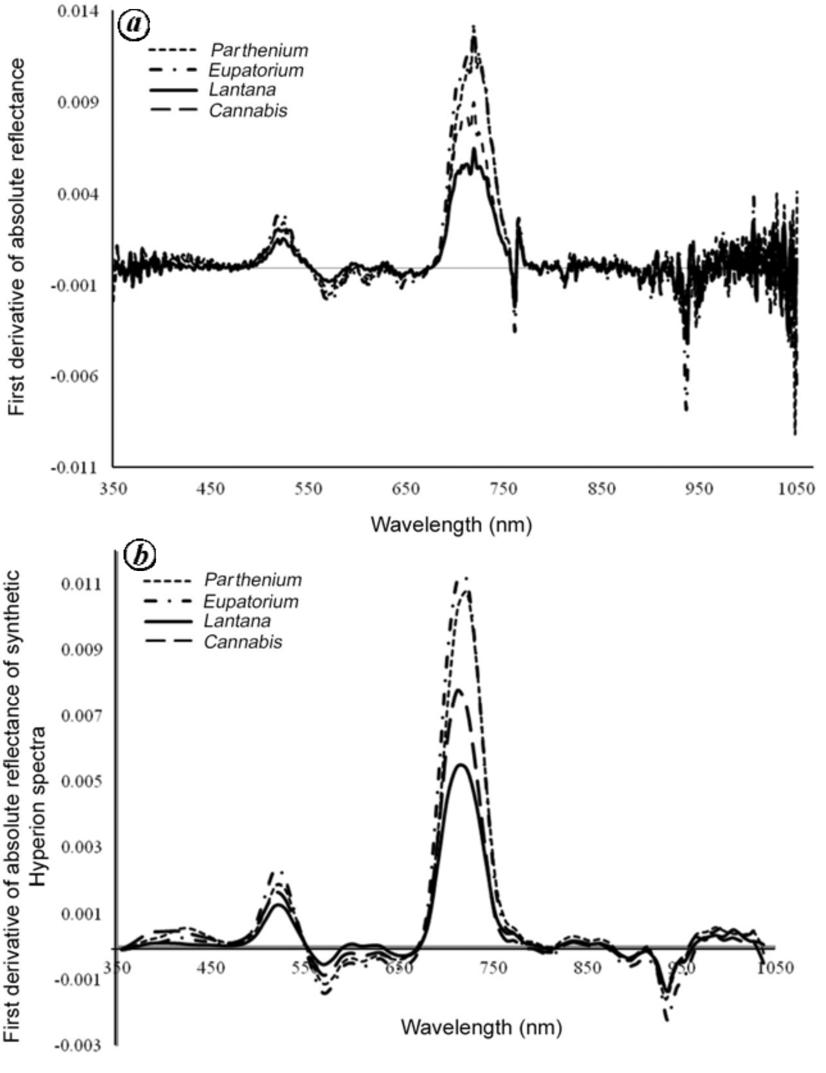

Figure 2. First derivative of the original spectra (***a***) and synthetic spectra (***b***) of the target species.

Table 1. Spectral angle mapper (SAM) analysis: spectral difference of other species w.r.t. *Lantana* using absolute reflectance (AR) and first derivative (1st D)

	Original spectra				Synthetic spectra			
	SAM value		Equivalent angle		SAM value		Equivalent angle	
Species	AR	1st D	AR	1st D	SynH	1st D	SynH	1st D
Parthenium	0.963	0.708	15.635	44.928	0.967	0.901	14.76	25.71
Eupatorium	0.947	0.648	18.738	49.61	0.957	0.852	16.863	31.57
Cannabis	0.89	0.644	27.127	49.91	0.909	0.851	24.632	31.68

SAM value as cos θ and equivalent angle in degrees. SynH, Synthetic Hyperion spectra.

response pattern. To assess the capability of spectral wavelengths of Hyperion for such applications, SynH was generated from AR using wavelength (350–1050 nm) and FWHM information (corresponding to wavelength) by spectral convolution.

For mapping types of invasive species over a large geographic area, it is recommended to use hyperspectral remote sensing data. Having more number of bands with narrow wavelength interval enhances the capability to differentiate the plant species[17]. Among the remote sensing community, importance of hyperspectral remote sensing data is well appreciated. But there are few sensors which are dedicated to capture information using such spectral resolution. In the present constellation of space-borne satellite, EO-1 Hyperion is the only sensor providing such datasets. Few of the developed countries have the privilege of capturing such information using airborne sensors. In India, this practice is a challenge because of surveying restrictions using aerial platforms. Such studies will help prioritize hyperspectral remote sensing systems in the forthcoming launches. This is important when habitat fragmentation due to invasive species is at its peak and many new changes are expected. Moreover, having a database on the phyto-diverse landscapes demands frequent and rapid identification and mapping of species. Hyperspectral remote sensing tools will not replace but certainly contribute to laboratory-based measurements for identification of plant species.

1. Vitousek, P., Loope, L., D'Antonio, C. and Hassol, S. J., In *Elements of Change, 1994* (eds Hassol, S. J. and Katsenberger, J.), Aspen Global Change Institute, Aspen, Colorado, USA, 1995, pp. 213–336.
2. USDA Forest Service Invasive Species Program; http://www.fs.fed.us/invasive-species/index.shtml (last modified: Tuesday 8 March 2011).
3. Boswell, C. C. and Espie, P. R., *N. Z. J. Agric. Res*., 1998, **41**, 251–261.
4. Levine, J. M., Pachepsky, E., Kendall, B. E., Yelenik, S. G. and Lambers, J. H. R., *Ecol. Lett*., 2006, **9**, 1005–1014.
5. Levin, D., *Syst. Bot*., 2003, **28**, 643–650.
6. Sharma, G. P. and Raghubanshi, A. S., *Appl. Soil Ecol*., 2009, **42**, 134–140.
7. Dobhal, P. K., Kohli, R. K. and Batish, D. R., *J. Ecol. Nat. Environ*., 2011, **3**, 11–22.
8. Asner, G. P. and Vitousek, P. M., *Proc. Natl. Acad. Sci. USA*, 2005, **102**, 4383–4386.
9. Andrew, M. E. and Ustin, S. L., *Remote Sensing Environ*., 2008, **112**, 4301–4317.
10. Masocha, M. and Skidmore, A. K., *Int. J. Appl. Earth Obs. Geoinf*., 2011, **13**, 487–494.
11. Joshi, C., DeLeeuw, J., van Andel, J., Skidmore, A. K., Lekhak, H. D., van Duren, I. C. and Norbu, N., *For. Ecol. Manage*., 2006, **1**, 245–256.
12. Shaw, G. A. and Burke, H. K., *Lincoln Lab. J*., 2003, **14**, 3–28.
13. Milton, E. J., Schaepman, M. E., Anderson, K., Kneubühler, M. and Fox, N., *Remote Sensing Environ*. (*Suppl. 1*), 2009, **113**, S92–S109.
14. ASD Inc., http://www.asdi.com/ (accessed on 5 May 2012).
15. Jensen, J. R., *Introductory Digital Image Processing: A Remote Sensing Perspective*, Prentice Hall, 2004, 3rd edn.
16. Broadman, J. W. and Kruse, F. A., In Proceedings, 10th Thematic Conference on Geologic Remote Sensing, Environmental Research Institute of Michigan, Ann Arbor, USA, 1994, vol. I, pp. 407–418.
17. Im, J. and Jensen, J. R., *Geogr. Compass*, 2008, **2**, 1943–1961.

ACKNOWLEDGEMENTS. A.G. thanks the Council of Scientific and Industrial Research, New Delhi for support. We thank TERI University for providing experimental and computational facilities and the anonymous reviewers for constructive comments and suggestions that helped improve the manuscript.

Received 11 June 2012; revised accepted 14 March 2013

ANIRUDDHA GHOSH[1]
P. K. JOSHI[1,*]
R. D. GARG[2]
SANDIP MUKHERJEE[1]

[1]*Department of Natural Resources, TERI University, Vasant Kunj, New Delhi 110 070, India*
[2]*Department of Civil Engineering, Indian Institute of Technology, Roorkee 247 667, India*
**For correspondence.*
e-mail: pkjoshi@teri.res.in