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THE JOINT FORCES OF CSIRO & SCION

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CLIENT REPORT No: 38641

EXECUTIVE SUMMARY

Objective

This project evaluated remote sensing technologies with potential to provide data and solutions for forest health issues.

Key Results

An industry review identified key forest health issues that were of relevance to remote sensing: foliage disorders (i.e. Dothistroma, Cyclaneusma), part or total tree impacts (nutrient deficiencies, mortality, forest health condition) and non-tree competitors (weeds). Many technologies were evaluated, including photography, visual assessment, hyperspectral and multispectral data acquisition, and LIDAR.

The combination of hyperspectral data and LIDAR appear to offer the greatest potential to map and characterise distribution of weeds and foliar diseases. They could also be used for assessing crown health. Mortality can be accurately mapped using a variety of methods. Digital sketchmapping should be examined in more detail, as it appears to be an excellent measure for collecting data on disease outbreaks and weed infestation in the interim until spectral data become more accurate.

The major constraints to implementation of remote sensing for forestry have been the cost of data collection and processing coupled with the lower level of accuracy and precision compared with what could be obtained using traditional methods. The role of remote sensing in forest health management is expected to mature and hence become more feasible operationally in the next 10 to 15 years.

Remote sensing does provide enormous potential to collect forest health data objectively, accurately, and cheaply. Research effort should be made to expedite the time when Dothistroma needle blight, for instance, can be mapped with sufficient accuracy to enable sound decisions on control measures to be made.

Application of Results

The technologies identified as having the best potential should be tested on target disorders. A research programme needs to be developed based on the results of this study.

Further Work

Prepare a research programme, consult with interested parties, and then start field trials.

CLIENT REPORT No: 38641

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Contract number	
Client Report No.	38641
Products investigated	Remote sensing technologies
Wood species worked on	Pinus radiata
Other materials used	Forest Health
Location	

INTRODUCTION

The FBRC and FRST co-funded this remote sensing project with the primary objective of determining remote sensing technologies that could be used to assist with forest health issues. The scope of the project encompassed the broadest definition of forest health and remote sensing.

The project comprised two parts. Firstly, industry needs with regard to forest health issues were identified by means of a review. Then, remote sensing technologies were identified and evaluated with regard to these industry needs. This report describes the outcomes from the identification and evaluation process.

MATERIALS AND METHODS

The industry review stage was carried out from May to June 2005. Seven key industry people involved with forest health were interviewed, along with other industry people who were consulted on an *ad hoc* basis. The review identified a number of key forest health issues (*see* Bulman 2005 for full details). The most important issues are shown in Table 1.

Table 1 – Key forest health issues identified during the industry interview stage

Issue	Type
Dothistroma	Foliage
Cyclaneusma	Foliage
Physiological needle blight (PNB)	Foliage
UMCY	Foliage
Nutrient deficiencies	Foliage, part or entire tree
Wind damage/branch breakage	Entire or part tree
Hylastes/seedling/ Armillaria mortality	Entire tree
Overall forest health score	Entire tree
Crown density/forest condition monitoring	Entire tree
Weeds	Non tree competitors

The key issues could be grouped into types: i.e. foliage disorders, entire tree impacts, part tree impacts, or non tree competitors. It was decided to use a symptom-based approach rather than a disorder-based approach for the evaluation stage. For instance, Dothistroma needle blight, Cyclaneusma needle-cast, and PNB are all different disorders but cause broadly similar symptoms – dead or dying foliage. It is likely that technologies selected for evaluation for use on each of the three disorders would be similar.

For evaluation purposes the issues were grouped into the categories shown in Table 2.

Table 2 – Key forest health issues categorised for evaluation

Category	Issue
Foliage disorders	Dothistroma
Foliage disorders	Cyclaneusma
Foliage disorders	Physiological needle blight (PNB)
Foliage disorders	UMCY
Foliage disorders	Nutrient deficiencies
Competitor effects	Weeds
Entire tree	Hylastes/seedling/ Armillaria mortality
Entire or part tree	Wind damage/branch breakage
Stand level health	Overall forest health score
Stand level health	Crown density/forest condition monitoring

Technologies for each of the categories were identified and then evaluated in terms of cost, effectiveness, and application. Technologies evaluated are shown in Table 3. Specific systems are described in the Appendix.

Table 3 – Technologies evaluated

Issue	Technology	Target forest health parameter
Foliage disorders	Ground assessment	Dothistroma
	Aerial assessment – fixed-wing	Dothistroma
	Aerial assessment – helicopter	Dothistroma
	Aerial photography – large format	Cyclaneusma
	Aerial photography – medium format	Cyclaneusma
	Aerial photography – small format	Cyclaneusma
	Airborne video	
	Hyperspectral CASI-2	Dothistroma
	Multispectral CASI	Phellinus Root rot
	Digital sketch mapping	
Total mortality	Ground assessment	Armillaria
	Aerial assessment	Armillaria
	Aerial photography – large format	Armillaria
	Aerial photography – medium format	Armillaria
	Aerial photography – small format	Armillaria
	Hyperspectral CASI-2	Sphaeropsis
	Airborne video	
	Digital multispectral camera	Armillaria
	High resolution multispectral	Sirex mortality
	Digital multispectral camera	Sphaeropsis
Forest Health score	LiDAR	Crown density
Weeds	Hyperspectral	
	Hyperspectral Hyperion EO1 satellite	
	Digital sketch mapping	

RESULTS AND DISCUSSION

Foliage disorders

Hyperspectral and multispectral techniques

Dothistroma pini

A study to examine leaf reflectance spectra of *Pinus radiata* needles affected by Dothistroma needle-blight in order to identify wavelengths sensitive to symptoms was started in 2000 (Stone *et al.* 2003). The study showed that reflectance was correlated with needle damage (best ratio was 709/691 nm with r = -0.74) and that this showed promise in classifying Dothistroma damage on needles.

Coops *et al.* (2003) carried out a trial in 2001 where hyperspectral data from two sites were acquired using a CASI-2 spectrograph (Compact Airborne Spectrographic Imager). Both sites had trees displaying a broad range of Dothistroma disease levels. Trees were assessed from the ground using a 1-6 scale (no infection and then 20% steps). Various spectral indices were evaluated and the most promising, having significant correlation between mean crown spectra and needle-blight score, were included for further analysis. Correlations between ground-based severity scores and three spectral indices derived using a “halo” method ranged between R^2 = 0.51 and 0.55. Crown-scale reflectance measurements derived from different approaches were then tested for accuracy.

The best method could generally differentiate between severity classes, with the exception of distinguishing between severity classes 3 and 4 (21-40% and 41-60%). When the severity classification scheme was simplified into three classes, accuracy increased with all classes being assigned correctly at least 70% of all observations.

However, the benefit from using hyperspectral or multispectral techniques will arise not from assessment of individual trees, but of determining the average infection, or crown condition, over a particular area (Figs. 1 & 2). This may be an entire stand, or part of a stand or microsite. Accurate estimation and mapping of disease intensity at that level, integrated with a decision model, would prove extremely useful for determining areas to be treated during the annual Dothistroma spray programme. More work needs to be done to realise the potential benefits arising from spectral imagery.

Fig. 1 – An example of mapping disease from a multispectral image (from Mohammed *et al.*)

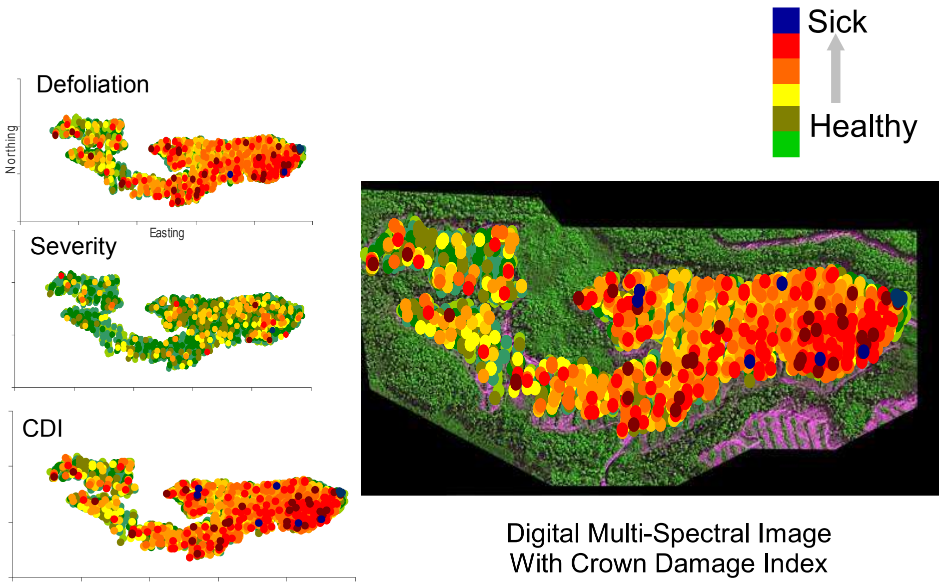
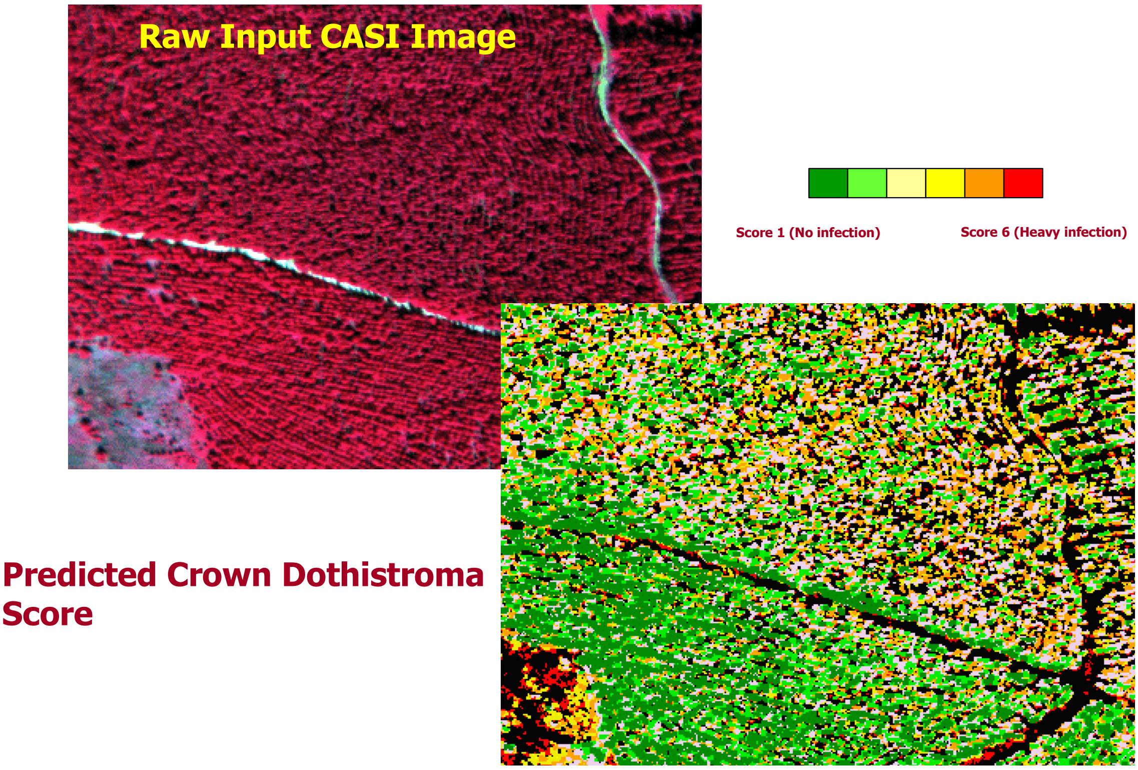


Fig. 2 – An example of output from a CASI image



Foliage symptoms from root disease

Leckie *et al.* 2004 tested the ability of multispectral imagery acquired with CASI to locate and assess trees infected by *Phellinus weirii*. Using classifications of healthy, light-healthy, light, moderate, severe, 100% needle loss, snag, and shadowed snag accuracy was in the order of 55-60% but there was significant confusion among the light to moderate classes. Using broader severity classes, average accuracies were 82% if a tolerance of ±1 class was tolerated. It was concluded that high resolution multispectral imagery combined with automated procedures appeared to be viable for detecting disease centres where severe symptoms were present.

Total foliage mortality

Mortality assessments using imagery are more accurate because the model needs only to classify crowns as alive or dead. This was demonstrated by Stone *et al.* (2004) where multispectral imagery was acquired by a digital multispectral camera. The images were calibrated to reflectance values using large white sheets as controls. Overall accuracy for determining Diplodia infection where the two classes were 0-40% and 41-100% was 96%. Of the 58 trees in the first class 57 were correctly predicted, and of the 40 trees in the second class 37 were correctly predicted. This result shows that multispectral imagery could accurately predict mortality from diseases such as Diplodia whorl canker, Hylastes bark beetle attack, or Armillaria root rot, because assessments would be distinguishing severity at or near 100% compared with severity at or near 0%. However, Ismail *et al*. 2006 were not quite as successful with using multispectral techniques to determine mortality due to *Sirex noctilio*. They found statistically significant differences ($P<0.001$) between healthy or green trees and those with visual symptoms (dead or long dead trees). Producer accuracy was 84% for red trees – i.e. of the trees that were identified as being red on the ground, 84% were identified as red using high resolution multispectral imagery. The remaining trees were identified as being either healthy or long dead.

Cost

Collection and interpretation of data from CASI 2 is approximately $1.50/ha. Multispectral imagery can be collected for about $0.90/ha.

Visual aerial and ground assessment

Accuracy

Visual assessment of foliar diseases can be done in several ways. In New Zealand, individual trees are scored in 5% steps, where the percentage of unsuppressed crown that is diseased is estimated (Bulman *et al.* 2004). Prior to that, a 0-7 scoring system was used, after a modified logarithmic scale based on the Horsfall-Barrett system for measuring disease in agronomy (Horsfall 1945). The percentage step system is accurate, provided assessors are skilled and experienced. Van der Pas *et al.* (1984) reported that the standard error of a ground assessment of 100 trees with an average disease level of 40% is in the order of 5%, i.e. within the range of 35-45%. For assessment from the air, standard error increased to about 8%, i.e. for one assessment of two stands a 40% rating will be in the range of 32-48%.

Assessing mortality caused by Hylastes bark beetle or Armillaria root rot is simpler than assessing variable damage such as that caused by Dothistroma needle blight or Cyclaneusma needle-cast. This is because mortality results in total foliage death, and therefore assessment of disease severity on individual trees is not required. The only assessment required is incidence (the percentage of individuals affected). Needle cast assessment necessitates assessment of severity and incidence. While no objective study of the accuracy of disease incidence assessments have been carried out, it is obvious that assessments from the ground of tree mortality on individual trees will be 100% accurate within the sample taken, as the assessor merely has to record whether the tree is alive or dead. From the air, accuracy will be lower, because the assessor has to assign a global figure for a stand.

Cost

Ground assessments of disease on individual trees are time consuming, and are generally done only for research purposes. An experienced observer can assess about 500-600 trees per day, depending on ground conditions and the layout of assessment plots. This equates to about 10 stands per day, if three 20-tree plots are assessed per stand. For a forest that comprises 100 stands the survey cost would be approximately $6,400 at a charge rate of $80 per hour, say 64c/ha if stands averaged 100 ha each. Another 5c/ha should be added for processing and digitising the data collected. Aerial surveys using fixed-wing aircraft are cheaper – 100 stands could be flown in about 4 hours for a cost of approximately $1,200 for an assessor and fixed-wing flying time, or 12c/ha plus 11c/ha for assessor time, digitising data and some ground truthing. For aerial surveys using helicopters costs are similar to ground surveys at about 53c/ha for the helicopter and 11c/ha for assessor time, digitising data and some ground truthing.

Aerial photography

Accuracy

Large format (23 cm x 23 cm) aerial photographs

Recent technological advances in large format camera design, improved film resolution and the availability of GPS-controlled navigation systems, has increased the versatility of aerial photography for forest health assessments.
A study by Firth *et al.* (2002) showed that symptoms caused by *Armillaria* species could be reliably identified and quantified on colour diapositives (transparencies) taken with a large format RC30 camera with forward motion compensation (FMC) fitted. The diapositives provided high resolution imagery with excellent colour rendition. When viewed under a stereoscope, the 1:3000 negative scale (taken at a flying height of 1200m) enabled reliable identification of individual 4 year old *Pinus radiata* infected by *Armillaria* sp. Of the dead trees, 96% were correctly identified from the photographs.

Cost

The coverage provided by one stereo pair of photographs was approximately 50 hectares. Direct costs are in the order of $90 per sampling point (cost includes helicopter, film, and printing). Assessment and processing costs in the office would add a further $60. Costs are therefore in the order of $3/ha. Processing costs for determining mortality would be slightly lower, as the assessor need only differentiate between healthy and dead trees. Cost is therefore reduced by 15% for mortality assessments.

Medium format (55 mm x 55 mm) aerial photographs

Where symptoms of disease are visible in the mid to lower canopy (e.g. Upper Mid-crown yellowing (UMCY), Dothistroma needle-blight, and Cyclaneusma needle cast) then an alternative to vertical aerial photography is required. Firth *et al.* (1997) developed a system using stereo interpretation of medium format, oblique, colour photographs taken looking into the crown at a 35 degree angle. A helicopter was used as the camera platform because of the need for high manoeuvrability and a low flying height requirement of 100 m. The combination of a navigator utilising a global positioning system (GPS) and the pilot using a radar altimeter enabled each photo site to be accurately and speedily located and the helicopter to be positioned at the correct height for the photography. Each stereo pair of images enabled approximately 30 trees to be assessed at each site. The average flying time, to fly to and photograph each site (a total of 300 sites), was 4 minutes.

Cost

Much the same as large format photographs, approximately $3/ha.

Small format (35 mm) film or digital photography

Another option for assessment of crown health is the use of 35mm frame cameras (either film or digital). Firth *et al.* (2004) demonstrated that, using a helicopter as the camera platform, such a system could be used to assess diseases such as Cyclaneusma needle-cast in radiata pine. Results indicated that colour, oblique, stereo images taken at a flying height of 600 m (Fig. 3), using a 200 mm focal length lens (photo scale 1:3000) would enable the incidence and severity of Cyclaneusma needle cast to be obtained with an accuracy comparable with field assessment, provided the assessor was experienced and skilled. The standard error from assessments of photographs was higher than that of ground assessments, by approximately 20-30%. The same technique could also be used for assessing Physiological needle-blight.

Fig. 3 - Oblique photograph taken from 600 m (from Firth *et al.*)

The recent advent of full frame (36 x 24 mm imager) digital cameras, used in conjunction with digital image, stereoscopic viewing systems (e.g. Stereographics Corp., Monitor Zscreen system), could offer new opportunities to assess canopy health from the air with benefits in terms of time and cost.

Cost

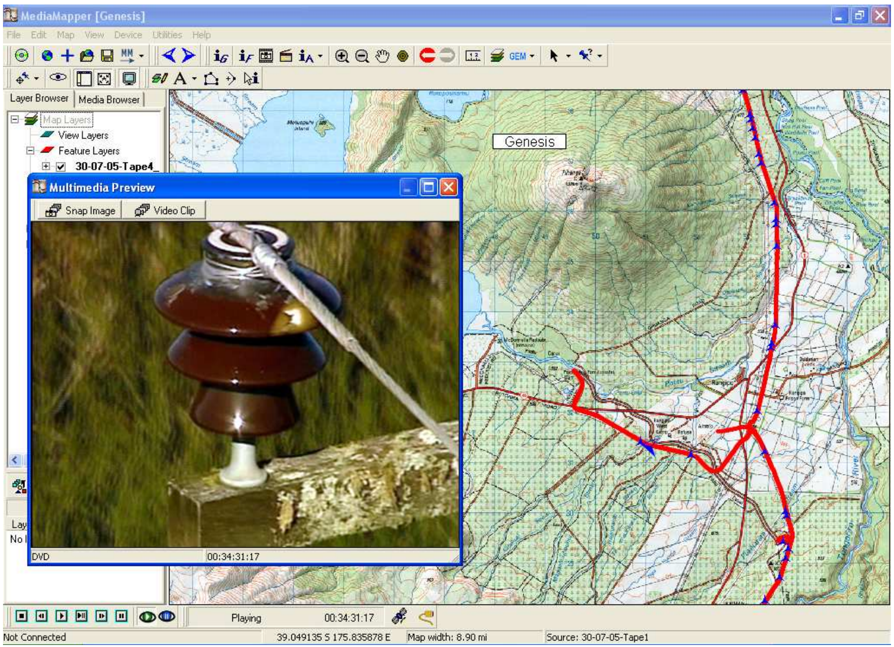
Slightly cheaper than the medium format photographs, $2.80/ha.

Airborne Video

Airborne video has been tried and tested for many years. Initially, Hosking (1993) evaluated airborne video for resource monitoring. After that publication was written, the technology was tested mainly for use over indigenous forests and Hosking wrote various internal Forest Research Institute reports on the subject. His primary conclusion was that the system showed promise and if it could be made to work there was huge potential for its use in forest health assessment of both indigenous and exotic forests. However, the technology available at the time was problematic. For instance, S-VHS imagery was compared with conventional aerial photography for the assessment of UMCY. The video resolution was significantly poorer than still images, mainly because of aircraft vibration and video camera technology. Other work was carried out with regard to coverage, resolution, camera, and aircraft set-up. The key finding was again that video imagery had potential for a wide range of uses but key areas needed research focus – specifically optimising image acquisition for specific applications to ensure high quality results.

Since the mid-1990s technology in this area has advanced markedly. The problem of aircraft vibration and mediocre resolution has been fixed due to gyro-stabilised cameras and high quality CCD (charge-coupled device) digital images (*see* Fig. 4). Image acquisition can be linked to extremely accurate GPS systems to allow rapid integration with other mapping layers. Good quality digital still photographs can also be taken, and then these photos imported and overlaid onto the video track log.

Fig. 4 – A screen grab of survey footage showing image and aircraft track log



Cost

Along with advances in technology, costs have decreased due to increased efficiency – i.e. wider swaths and higher aircraft speed tolerances for high quality image acquisition. Cost is very much dependent on economy of scale. Carrying out a very small 1-2 hour job is very expensive because set up costs with camera installation are high. Fixed costs are in the order of $4,000 per day, plus $1,750 per hour. However, a great deal of ground can be covered in that time and rates are negotiable for large jobs. Swath widths in the order of 150 m may be expected. If so, at a flight speed of 80 kph, approximately 1200 ha could be flown in an hour. Adding 10c/ha for data processing, costs are about $2.10 per ha at the maximum rate quoted.

Forest Health Score

LiDAR

LiDAR (Light Detection And Ranging) uses laser pulses to provide highly accurate measurements of height and spatial location of objects within forest canopy. A key strength of LiDAR is the ability to accurately record the spatial coordinates of detected surfaces (errors typically <0.15 vertically and 0.40 horizontally). As a result, LiDAR is well suited to monitoring applications and may be used to assess changes in the plant area as function of height.

Airborne LiDAR has most commonly been used to create digital terrain maps, but has more recently been used to determine canopy structure elements. A number of studies have demonstrated LiDAR can be used to quantify individual tree dimensions (*e.g.* tree height and crown area) and biomass (Riano *et al.* 2004), which themselves can be used to indicate plant condition. Riano *et al.* 2004 found that LiDAR data could be used to accurately estimate crown volume (R^2 = 0.92) and foliage biomass (R^2 = 0.84) to give an estimate of crown density at the plot level.

LiDAR plus multispectral

One of the key issues in remote sensing for crown condition assessment is the detection of trees with very thin crowns. Damaging agents such as the Essigella pine aphid, for example, cause crown defoliation which reduces the visibility of the tree in remotely sensed imagery. Forest health monitoring is founded on crown density scores, assessed visually from the ground. Woodlots and plantations can display a very large variation in crown density between individual trees. Increased light penetration through the relatively transparent crown can increase the vigour of understorey species. As a result, it is easy to misidentify pixels in multispectral images over heavily defoliated trees as being in good condition, thus increasing error associated with assigning a "global" crown health score to a group of trees.

These errors could be minimised by incorporating LiDAR data with high resolution multispectral imagery, which would enable the canopy to be stratified by height. Pixel values in multispectral images could be weighted by the proportion of LiDAR points at canopy level. Alternatively, the crown scale height variance of LiDAR points alone might be sufficient to identify highly transparent crowns.

The integration or fusion of LiDAR and optical data has the potential to complement deficiencies of the alternate technology as well as improve the accuracy of forest health assessments.

For example, Blackburn (2002) investigated the use of LiDAR data to locate canopy gaps and subsequently remove these areas from CASI imagery to improve the quantification of forest pigment content, and McCombs *et al.* (2003) examined the benefits of fusing LiDAR with airborne multispectral data. McCombs *et al.* showed tree identification was superior using the combined dataset over both spectral and LiDAR data used individually, while the delineation of tree crowns was better using multispectral imagery than LiDAR data alone. By removing non-target vegetation from analysis it is likely the accuracy of a range of forest health assessments based on passive optical remote sensing may be improved. These datasets are not commonly available at this time, however.

Cost

The price per hectare will be highly dependent on the sensor configuration used. Higher platform altitudes and scan angles (measured off nadir) will survey a greater area across track and reduce the acquisition costs. However, for a fixed pulse frequency the posting density will be reduced which may reduce the accuracy of computed metrics. An approximate average cost will be in the order of $70 000 for 6 hrs flying time. LiDAR may be effective at a swath of up to 0.7 altitude. Assuming a flight of 500 m agl the swath is 350 m. If so, at a flight speed of 80 kph, approximately 2800 ha could be flown in an hour. Costs were therefore about $4.20 per ha. In another study, it cost $70,000 to acquire data covering 12,600 ha which equates to $5.50/ha.

Weeds - Spectral Separability of Plants: Detection of Weeds within Planted Forests

Geological remote sensing has provided the expectation that given spectral measurement of sufficient purity, it should be possible to remotely identify vegetation types. Actually, the real world provides confounding factors such as view angle, target purity (vegetation is made up of different reflective surfaces and material, as well as problems associated with vegetation canopy transparency and the incidental imaging of non-plant material), atmospherics and illumination. Okin *et al.* (2001) showed that low canopy cover situations, phenological variation, and variable soil/geologic background have limited the identification of plants. Price (1994) suggests that several plants may have similar signatures due to the variability in signatures within a species, and that the spectral signature is a result of a few independent variables. In short, the reflectance spectra from plants are highly correlated with each other, and are probably not unique.

Within the literature, research is focused on identifying the location or density of different species within a community or mono-culture, primarily for the detection of weeds within an established crop and the detection of exotic species within a natural ecosystem. Additionally, significant research has been undertaken in the classification of forest types but this is not considered in this review as it has no applicability to New Zealand plantation forestry. Research focuses on identifying differences in vegetation where there is *a prior* knowledge of species composition, or the identification of specific species, rather than absolute identification of all species present. As well there are other confounding factors such as differentiating age classes; vegetation cover classes etc.

In a review paper, Joshi *et al.* 2004 shows that in 2001 approximately 80 publications were on remote sensing and using GIS to produce invasive species maps, with approximately 70 each in the 2 preceding years. The review notes that most of the research has been in canopy dominating species, mixed canopy species, with smaller number of papers in a “invaders influencing canopy dominate species” context. Only one paper is referenced for understorey species.

The spectral separation of species, by leaf, under laboratory conditions, (i.e. using a hand held spectrophotometer, with constant lighting, and spectrally homogeneous samples) is well reported in the literature, though primarily in agricultural crops: e.g.:

- Sicklepod, Pitted Morning Glory, Entire Leaf Morning Glory and Common Cocklebur can be distinguished from each other (LeMastus *et al.* 2000)
- Sicklepod, Pitted Morning Glory, and Horsenettle can be identified with soybean (Medlin *et al.* 2000)
- Sorghum identified in Cotton (Richardson *et al.* 1985)
- Vrindts *et al.* 1999 completed weed detection of 14 weeds with 4 different agricultural crops and demonstrated statistically that leaves between crops and weeds can be discriminated.

Satellite

Peters *et al.* (1992) used a low-resolution satellite (1.1 km sq pixel) with two time periods aimed at the spring flush and later during flowering, to detect successfully Broom snakeweed in grasslands.

In more natural landscapes, Ustin *et al.* (2001) and Underwood *et al.* (2006a), Underwood *et al.* (2006b), and DiPietro (2002) tested the use of airborne spectrophotometer at 4m resolution to map invasive species (iceplant, jubata grass, fennel, blue gum and giant reed) in coastal natural ecosystems (scrub-lands, riparian woodlands and chaparral). High classification accuracies (82-100%) were obtained in the riparian and grasslands with accuracies in the riparian wood lands, while accuracies dropped for prediction of density classes of iceplant, the overall accuracy was 75%. Consistent spectral and textual differences between the native and the invasive species did allow accurate classification.

Landsat studies (30m pixels) have been unable to detect spectral differences in community type in chaparral systems (Westman and Price 1988), but other studies have shown that 20m hyperspectral data can be used (Roberts *et al.* 1998, Garcia and Ustin 2001).

A larger scale project to map Chinese tallow tree within native communities was undertaken by Ramsey *et al.* 2005a, 2005b, and 2005c), using the Hyperion hyperspectral satellite (30 * 30m pixel size). The goals were to provide regional monitoring while being able to detect occurrences smaller than the resolution of the satellite, and to detect low-percentage occurrences of the plant estimated to a 2% average reflectance difference - equating to a canopy spatial area of 12*12m. The detection levels obtained suggest that tallow of less than 10% pixel composition was detected 68% of the time and 15% compositions were detected 85% of the time.

Multispectral and hyperspectral

Smith and Blackshaw (2003) demonstrated weed-crop discrimination at a leaf level and showed that with using hyperspectral data, plants of similar types (e.g. grasses or broadleaves) would be incorrectly classified; and when using multispectral data the mix classifications crossed type boundaries (i.e. grass classified as broadleaf and vice versa). In forested landscapes, Roberts (2004 *et al.*) report that in mixed broadleaf and conifer forests of the Pacific Northwest, discrimination between plant species is most evident at a branch scale. At the stand scale, only conifers and broadleafs and conifer age classes were spectrally distinct although the differences between branch scale and stand scale results is confounded by the large change in the spatial resolution of the sensors used: branch scale - 38 cm radius; canopy scale 400 m^2; and also the effects of illumination and canopy structure. They state that “Branch scale analysis suggests that, given a spatial resolution fine enough to resolve individual crowns, species can be separated”. Also, the analysis of the hyperspectral data was limited to pixels that contained pure stands, and no analysis was undertaken to quantify sub-pixel species separability.

Gong *et al.* (1997) tested ground based hyperspectral data for conifer species separation with good results (up to 91% accuracy). Martin *et al.* (1998) used an airborne sensor to discriminate between 11 forest cover species with accuracies up to 75%. Niemann (1995) was able to separate Douglas fir forest into 2 age classes.

Van Aardt (2000) demonstrated that using canopy measures of reflectance spectral discrimination between deciduous and coniferous trees was very successful, ranging from 97.7 to 100% accuracy. In simulated (i.e. ground reflectance data was degraded in spectral resolution to match the airborne sensor) airborne sensor data 100% discrimination was found.

Clark *et al.* (2005) showed that 100% of the seven tropical emergent tree species at leaf scales could be spectral separated; at crown levels they shown high separation with using sun-lit crown pixel level (88%) and at 92% when sunlit portions of individual tree crowns were averaged into one pixel. The portions of the spectrum that were important for the crown level are the visible (400-700 nm) and SWIR (Short-Wave Infrared: 1994-2435 nm). The other critical factor is the very high resolution of the imagery in relation to individual crown size (1.6sq.m pixel with the average crown being 444 m^2).

To improve the spectral separability of plant species, researchers have timed image capture to utilise phenological differences between target species or differences over time, e.g. flowering. Leafy spurge (Everitt and Anderson 1995) yellow starthistle (Lass *et al.* 1996, 2000), yellow hawkweed (Lass *et al.* 1997) have been mapped based on bract or inflorescence colour.

Sprehe (2005) used a two image approach, using hyperspectral imagery in spring, with standard digital camera imagery in autumn. No species separability was found in her study, but this was probably due to the lack of resolution in the hyperspectral imagery.

Lass *et al.* (2002) successfully tested the distribution of spotted knapweed in different cover types including forests. In the Everglades the Brazilian pepper tree distribution was evaluated, with limited success, where large infestations where mapped successfully, but sparse populations where not mapped well at all (Lass & Prather 2004). In another study, Lass (Lass *et al.* 2000), tested the relationship between spatial resolution and phenology, with 4m sq pixels during flowering of yellow starthistle performed better that 0.5m sq pixels when no flowers were present.

Leafy Spurge was detected within natural vegetation (including woody vegetation) some success using 20m pixel hyperspectral airborne sensor AVIRIS in 6 classes of infestation. They estimate that they can detect infestation to approx 95% accuracy at a 0.10 threshold (Parker Williams and Hunt 2002).

Digital sketch mapping

As shown above, using digital imagery to delimitate weed infestations has some disadvantages. For instance, there are difficulties distinguishing weeds from their surroundings and sometimes imagery must be collected within a narrow time frame when phonological characteristics, i.e. flowers, are present. Sketch mappers can detect and monitor pest outbreaks and weeds accurately for relatively low cost. Experienced observers can distinguish between different diseases such as Armillaria root rot, Dothistroma needle blight, and Cyclaneusma needle cast; or weeds such as gorse or broom. Inaccuracies arise not from confusion between diseases or weed species but from confusion on precise location, particularly when surveying large areas on contiguous even-aged forests. It was difficult keeping track of exact position when sketching on paper maps.

This problem has been solved by the advent of digital sketch mapping. Geolink software and GPS, combined with a laptop, touchscreen, and stylist, allow weed and disease infestations to be directly sketched in real time. Surveyors draw infestations directly onto a touchscreen, creating shapefiles as they go (Fig. 5).

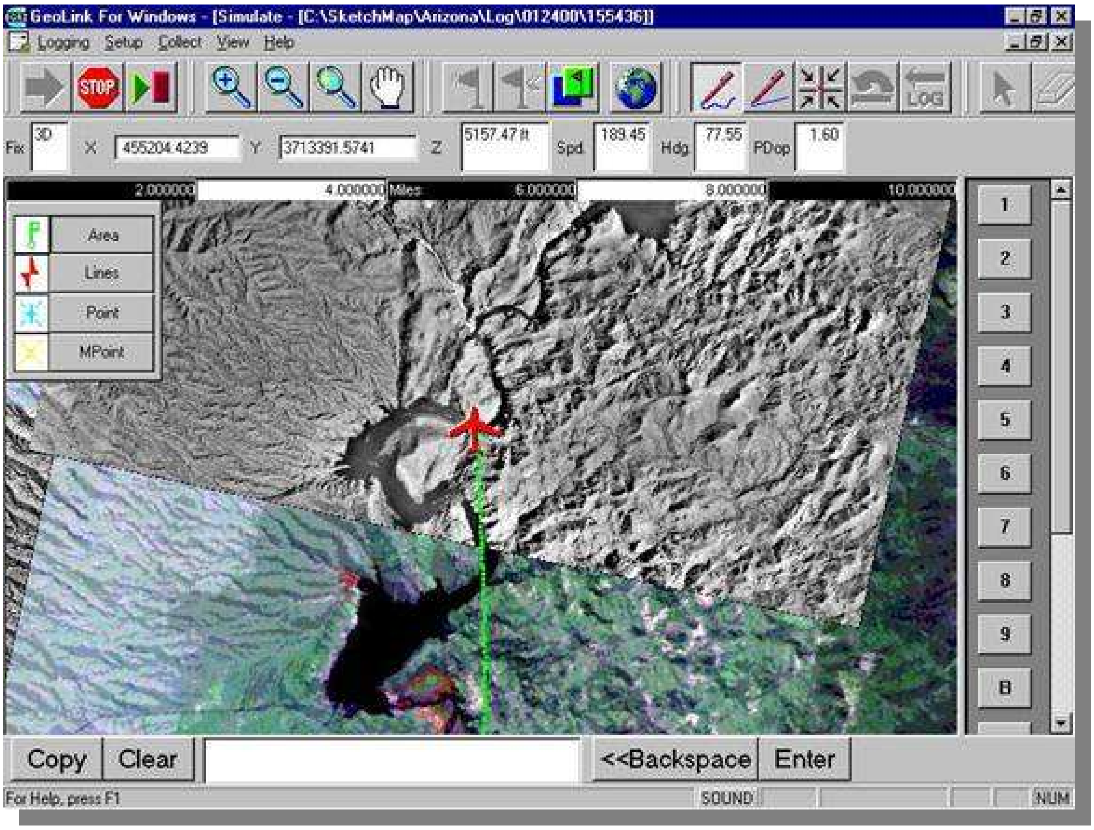
Fig 5 – Tablet with integrated GPS use to map infestations (courtesy of D. Wittwer, USDA Forest Service, Juneau, Alaska)

The prime disadvantage of sketch mapping compared with spectral remote sensing data acquisition techniques is that data collection is dependent on surveyors' interpretation. For instance, one person may combine many small areas of infestation into one large area, while another surveyor may attempt to preserve those small areas. Also, sketches are just that, and will not demarcate the edges of infestation as accurately as, for instance, an aerial photograph.

Cost.

Cost estimates vary from 1c per hectare for fixed-wing surveys over large areas (Dustin Wittwer, pers. comm.) to $0.50-1.70 per hectare for weed survey work in Oregon using a helicopter (Schrader-Patton 2006).

Fig. 6 – Screen grab of view on tablet showing aircraft position and input data. Infestation type buttons (coded) are on the RHS. The surveyor clicks on the appropriate infestation type and then draws the infestation area on screen (courtesy of D. Wittwer).



Application to New Zealand conditions

The spectral separability of weeds, even in tree crops, is governed by the spectral and textural differences between radiata pine and the common weeds found in forests (e.g. broom, pampas, gorse); the difference in crown size and density, and by the using phenology to enhance spectral differences. Limiting factors would be the position of weed species within the canopy (i.e. canopy, sub-canopy, understorey) which is related also to the age of the trees.

The improvement in the last few years has been due to the increased availability of hyperspectral imagery and some advanced processing of the data. The successful identification of small areas of Chinese tallow within forests by Ramsey *et al.* (2005) is significant and encouraging.

Cost

No estimation of costs is provided. The costs for the use of hyperspectral equipment would be the same as seen for Dothistroma detection. It is noted though, that only some analytical techniques require a large set of narrow band reflectances.

Options for further weed research

- Confirm the expected spectral difference between weed species at the leaf scale.
- Evaluate whether the CASI data collected in 2003 could be used to detect the location and density of pampas/broom within the stands flown in Te Matai Forest. The assumption is that the location of pampas and broom will not have changed in the intervening years, though new plants may have come after thinning.
- Evaluate the use of Hyperion to quantify weed density classes within young stands i.e. where the tree crowns are not closed
- Evaluate the use of digital camera systems to detect weeds.

Table 4 summarises accuracy and cost of techniques that could be used for various forest health conditions. It should be noted that the accuracy figures are generally best case examples and such accuracy may not be achieved in operational situations.

Table 4 – Summary of accuracy and cost of technologies evaluated

Issue	Technology	Accuracy - incidence	Cost ($/ha)	Target forest health parameter
Foliage disease	Ground assessment	95% correct ±5%	0.69	Dothistroma
	Aerial assessment – fixed-wing	95% correct ±8%	0.23	Dothistroma
	Aerial assessment – helicopter	95% correct ±8%	0.64	Dothistroma
	Aerial photography – large format	n/a	3.00	Cyclaneusma
	Aerial photography – medium format	n/a	3.00	Cyclaneusma
	Aerial photography – small format	±8-10%	2.80	Cyclaneusma
	Airborne video	95% correct ±15%	2.10	
	Hyperspectral CASI-2	~70% correct at 3 classes (low, medium, and high) 24-40% correct when assessing at 5 classes.	1.50	Dothistroma
	Multispectral CASI	55-60% but significant confusion among the light to moderate classes. 82% if ±1 class was tolerated	?	Phellinus Root rot
Total mortality	Ground assessment	100% correct	0.64	Armillaria
	Aerial assessment	95% correct ±10%	0.18	Armillaria
	Aerial photography – large format	96% correct	2.70	Armillaria
	Aerial photography – medium format	n/a	2.70	Armillaria
	Aerial photography – small format	n/a	2.40	Armillaria
	Hyperspectral CASI-2	96% correct distinguishing lead and dead	1.50	Sphaeropsis
	Airborne video	100% correct	2.10	
	Digital multispectral camera	96% correct	0.90	Armillaria
	High resolution multispectral	84% correct when comparing dead with healthy or long dead.	0.90	Sirex mortality
	Digital multispectral camera	96% correct between two classes – 0-40% and 41-100% of crown affected.	0.90	Sphaeropsis
Forest Health score	LiDAR	±30% on *Pinus sylvestris*	4.20	Crown density accuracy may be improved with the addition of multispectral data
Weeds	Hyperspectral	95% accurate in 10% steps for leafy spurge in a pastured setting. 11 forest cover species with accuracies up to 75%.		Overseas research has shown that high accuracies are possible, but no work has been undertaken on *P. radiata.*
	Hyperspectral	5% accuracy for 6 classes		Leafy spurge in natural forests
	Hyperspectral Hyperion EO1 satellite	95% accurate for mapping tallow trees in one study. In another, 68% to 85%, depending on pixel composition.		

RECOMMENDATIONS

The role of remote sensing in forest management is expected to mature and hence, become more feasible operationally for forestry in the next 10 to 15 years. The major constraints to implementation within forestry have been the cost of data collection and processing coupled with the lower level of accuracy and precision compared with data that could be obtained using traditional methods. The cost of satellite data has fallen over the last decade and it is expected that this trend will continue. Small satellite operations have demonstrated the ability to launch cheap, functional satellites (e.g. TopSat); the cost of digital CCD/CMOS (complementary metal oxide semiconductor) cameras has declined considerably, and more importantly the investment in remote sensing satellite systems is expected to be $US1.4 billion in the next 10 years. Increasing competition within the international space providers and the investment of the US government into their private satellite sector to safeguard capability and development will ensure continued R&D spending.

Accuracy and precision of space based and airborne systems has increased considerably due to:

(i) Significantly higher spatial resolution data availability from 25m to 0.60m over recent times.
(ii) Significantly higher spectral resolution data, particularly in hyperspectral systems.
(iii) The success of the Hyperion Hyperspectral satellite has demonstrated the usefulness and requirements for such systems.
(iv) The success of LiDAR and radar interferometry for a wide range of applications.
(v) The advancement of algorithms for processing data, including inversion of light/radar canopy and leaf interception models, statistical processing especially in data fusion, sub-pixel data extraction, atmospheric correction.

The remote sensing technologies that have application to Forest Health in the near- to long-term range are:

Hyperspectral Remote Sensing

Remote sensing technology can be expected to be used operationally for the detection and quantification of stress impacts, the detection of different species, and measuring / monitoring canopy condition within the next 10-15 years.

LiDAR

LiDAR, while more useful for estimating structural parameters of forest, could be used in determining canopy condition and transparency, particularly in conjunction with hyperspectral remote sensing techniques.

Radar

Similarity with LiDAR, the interaction of radar with the different components of the stands (needles, branches and stems) could be used for stressor and canopy condition modelling.

Research Recommendations

Industry support the research on satellite and airborne remote sensing technologies for solving problems of mapping and discriminating forest health problems, including disease severity mapping, weed mapping, and forest condition monitoring. Industry can show support by:

Support research programmes to Government e.g. RFI, SPS, TBG
Continue to provide access to forests and data for experimental work
Establish remote sensing as a theme within industry research groupings e.g. Future Forests Research

Research Issues

Long term Research

- Develop an understanding of optical interactions with canopies, in order to significantly improve the precision and accuracy of predicted parameters. This may include the development of light-canopy interaction models, the understanding of genetics on reflectance, the modelling of spatial distributions of trees (Dunningham pers. comm.).
- Develop more understanding on the light interaction with needles and the effect of needle damage on reflectance (Dunningham pers. comm.).

Medium Term to long term Research

- Explore the utility of radar interferometry for estimating the effects and severity of stress on trees.
- Development of aerial tools for the measurement of stress.

Short Term to Medium term Research

- Continue the leaf and seedling scale research into the spectral changes associated with different stressors (e.g pathogens other than Armillaria or Dothistroma) and linked in with research on nutritional deficiencies.
- Establish research projects on small trees, so as to understand the within variation of reflectance due to branching and needle distribution and density.

Test the effectiveness of remote sensing for the detection of forest weeds at various levels of accuracy

CONCLUSIONS

The application of remote sensing in forest management can be in several forms:

(i) The use of the technology as the primary data source of information.
(ii) The use of the technology to interpolate ground-based plot data so as to provide total forest coverage mapping of the health parameter of interest
(iii) The use of the technology as a primary data source, but as a sampling methodology providing a statistical estimate of a parameter. (e.g. current inventory – Cruiser / Marvl uses this methodology)

However, it is important to note that most remote sensing techniques are not yet there, with regards acceptable accuracy and cost competitiveness. A great deal of work needs to be done before remote sensing techniques can outperform traditional assessment and sketch mapping techniques.

Remote sensing does provide enormous potential to collect forest health data objectively, accurately, and cheaply. Research effort should be made to expedite the time when Dothistroma needle blight, for instance, can be mapped with sufficient accuracy to enable sound decisions on control measures to be made.

References

Blackburn, G. 2002. Remote sensing of forest pigments using airborne imaging spectrometer and LiDAR imagery. *Remote Sensing of Environment*, *82*, 311-321.

Bulman, L. S. 2005: Remote sensing needs identified during industry consultation. Ensis report 38165.

Bulman, L S; Gadgil, P D; Kershaw, D. J.; Ray, J. W. 2004: Assessment and control of Dothistroma needle-blight. Forest Research Bulletin No. 229, 48 p.

Clark M., Roberts D. and D. Clark. 2005: Hyperspectral discrimination of tropical rain forest tree species at leaf and crown scales. Remote Sensing of Environment 96():375-398.

Coops, N., Stanford, M., Old, K., Dudzinski, M., Culvenor, D., Stone, C. 2003: Assessment of Dothistroma needle blight of *Pinus radiata* using airborne hyperspectral imagery. Phytopathology 93:1524-1532.

DiPietro D. 2002: Mapping the Invasive Plant Arundo donax and associated riparian Vegetation using Hyperspectral Remote Sensing. Master of Arts Thesis. University of California, Davis.

Everitt J., Anderson G., Escobar D., R. Davis, N Spencer, and R. Andrascik. 1995: Use of remote sensing for detecting and mapping leafy spurge (Euphorbia esula). Weed Technology 9(3): 599-609.

Firth, J. G., Brownlie, R. K. 2002: Armillaria root disease of *Pinus radiata* in New Zealand. 5: Stand assessment using aerial photography. New Zealand Journal of Forestry Science 32(1):141-147(2002).

Firth, J. G., Brownlie, R. K., Olykan, S. T. 1997: Development of a large scale, aerial photograph technique to assess the severity of upper mid-crown yellowing (UMCY) in *Pinus radiata* trees. NZ Forestry 42 (1) 19-25.

Firth, J. G., Bulman, L. S., Brownlie, R. K. 2004: An aerial technique for assessing the severity of Cyclaneusma needle-cast in radiata pine. A Forest Research report prepared for the Forest Health Research Collaborative.

Ismail, R.; Mutanga, O.; and Bob, U. 2006: The use of high resolution airborne imagery for the detection of forest canopy damage caused by Sirex noctilio. *In* Ackerman PA, Längin DW & Antonides MC (Editors) 2006: Precision Forestry in plantations, semi-natural and natural forests. Proceedings of the International Precision

Forestry Symposium, Stellenbosch University, South Africa, March 2006. Stellenbosch University, Stellenbosch. ISBN: 0-7972-1121-7

Garcia M. and S. Ustin. 2001: Detection of interannual vegetation responses to climatic variability using AVIRIS data in a coastal savanna in California. IEEE Transactions on Geoscience and Remote Sensing 39:1480-1490.

Gong P. Pu R. and B. Yu. 1997: Conifer Species Recognition: An Exploratory Analysis of In Situ Hyperspectral Data. Remote Sensing of Environment 62:189-200.

Horsfall, J. G. 1945: "Fungicides and their action". Chronica Botanica Co., Waltham, Massachusetts. 239 p.

Hosking, G. P. 1993. Airborne video for resource monitoring – a new technology takes off. What's New in Forest Research No. 233.

Joshi C., De Leeuw J. and I van Duren. 2004: Remote sensing and GIS applications for mapping and spatial modeling of invasive species. XXth ISPRS Congress, 12-23 July 2004 Istanbul, Turkey Commission 7.

Lass L., and R. Callihan. 1997: The effect of phenological stage on detectability of yellow hawkweed (Hieracium pratense) and oxeye daisy (Chrysanthemum leucanthemum) with remote multispectral digital imagery. Weed Technology 11(2):248-256.

Lass L., Carson H., Callihan R. 1996: Detection of yellow starthistle (Centaurea solstitialis) and common St. Johnswort (Hypericum perforatum) with multispectral digital imagery. Weed technology 10(3):466-474.

Lass L. and T. Prather. 2004: Detecting the locations of Brazilian pepper trees in the Everglades with a hyperspectral scanner. Weed Technology 18:437-442.

Lass L., Thill D., Shaffi B., T. Prather. 2002: Detecting spotted knappweed with hyperspectral remote sensing technology. Weed Technology 16:426-432.

Lass L., Shafii B., Price William., D Thill. 2000: Assessing agreement in multispectral images of Yellow starthistle with ground truth data using a Bayesian Methodology. Weed Technology 14:539-544.

Leckie, D. G.;Jay, C.; Gougeon, F. A.;Sturrock, R. N.; and Paradine, D. 2004: Detection and assessment of trees with Phellinus weirii (laminated root rot) using high resolution multi-spectral imagery. International Journal of Remote Sensing 25(4):793 - 818.

LeMastus, F., Smith C., Shaw D. and R. King. 2000. Potential for weed species differentiation using remote sensing. CD-ROM Computer file. In P. Roberts et al. (ed). Proceedings of the 5th International Conference on Precision Agriculture. July 16-19 2000. Bloomington, MN. ASA-CSAA-SSSA, Madison WI.

Martin M., Newman J., Aber J. and R Congalton. 1998: Determining Forest Species Composition Using High Spectral Resolution Remote Sensing Data. Remote Sensing of Environment 65 249-254.

McCombs, J., Roberts, S., & Evans, D. 2003. Influence of fusing LiDAR and multispectral imagery on remotely sensed estimates of stand density and mean tree height in a managed loblolly pine plantation. *Forest Science*, *49*, 457-466.

Medlin C.R., Shaw P., Gerard P. and F. LeMastus 2000. Using remote sensing to detect weed infestations in Glycine max. Weed Science 48: 393-398.

Mohammed, C., Battaglia, M., Pinkard, L., Glen, M., Tommerup, I., Smith, A., Pietrzykowski, L., Barry, K., Eyles A., and Beadle. C. 2005. New tools for cost effective health management in eucalypt plantations. University of Tasmania and CSIRO Power point presentation.

Niemann, K., 1995. Remote Sensing of Forest Stand Age using Airborne Spectrometer Data. Photogrammetric Engineering and Remote Sensing 61 (9): 1119-1127.

Okin G., Roberts D., Murray B. and W. Okin. 2001: Practical limits on hyperspectral vegetation discrimination in arid and semiarid environments. Remote Sensing of Environment 77: 212-225.

Parker Williams A. and E.R. Hunt. 2002: Estimation of leafy spurge cover from Hyperspectral imagery using mixture tuned matched filtering. Remote Sensing of Environment 82:446-456.

Price J. 1994: How unique are spectral signatures. Remote Sensing of Environment 49:181-186.

Ramsey III E., Rangoonwala A., Nelson G., R. Ehrlich, K. Martella. 2005: Generation an validation of characteristic spectra from EO1 Hyperion image data for detecting the occurrence of the invasive species Chinese tallow. International Journal of Remote Sensing 26(8):1611-1636.

Ramsey III E., Rangoonwala A., Nelson G., R. Ehrlich. 2005: Mapping the invasive species, Chinese Tallow, with EO1 satellite Hyperion hyperspectral image data and relating tallow data to a classified Landsat TM land cover map. International Journal of Remote Sensing 26(8): 1637-1657.

Ramsey III E. and G. Nelson. 2005: A whole image approach using field measurements for transforming EO1 Hyperion hyperspectral data into canopy reflectance spectra. International Journal of Remote Sensing 26(8)1598-1610.

Riano, D., Chuvieco, E., Condes, S., Gonzalez-Matesanz, J., Ustin, S. 2004. Generation of crown bulk density for *Pinus sylvestris* L. from LiDAR. Remote Sensing of Environment 92, 345-352.

Roberts D., Gardner M., Church R., Ustin S.; Scheer G. and R. Green. 1998: Mapping Chaparral in the Santa Monica Mountains using Multiple Endmember Spectral Mixture Models. Remote Sensing of Environment 65:267-279.

Roberts D., Ustin S., Ogunjemiyo S., Greenburg J., Dobrowski S., Chen J., and T. Hinckley. 2004: Spectrl and Structural Meaures of Northwest Forest Vegetation at Leaf to Landscape Scales. Ecosystems 7: 545-562.

Richardson A., Menges R. and P. Nixon. 1985. Distinguishing weed from crop plants using video remote sensing. Photogrammetric Engineering and Remote Sensing. 51: 1785-1790.

Schrader-Patton, C. 2006: Digital Aerial Sketchmapping (DASM) for Invasive Weeds. www.fs.fed.us/eng/rsac/invasivespecies/documents/DASM.pdf

Smith A. and R. Blackshaw. 2003: Weed-Crop discrimination using remote sensing: A detached leaf experiment. Weed Technology 17:811-820.

Sprehe G. 2005: Application of phenology to assist in Hyperspectral species classification of a northern hardwood forest. MSc Rochester Institute of Technology NY.

Stone, C., Chisholm, L. A., McDonald, S. 2003: Spectral reflectance characteristics of Pinus radiata needles affected by dothistroma needle blight. Canadian Journal of Botany 81:560-569.

Stone, C., Coops, N., Sims, N., Ryan, P., Loughhead, A., Stanford, M., Goodwin, N. 2004: Application of Multispectral imagery to the management of pine plantation condition and productivity. FWPRDC report Project No. PN02.1906.

Underwood E., Mulitsch J., Greenburg M., S Whiting. 2006: Large Scale Mapping of Invasive Aquatic Vegetation in the Sacramento-San Joaquin Delta Using Hyperspectral Imagery.. Journal of Environmental Management. (In Press).

Underwood E., Ustin S., Ramirez C. 2006: A Comparison of spatial and spectral image resolution for mapping invasive plants in coastal California. Journal of Environmental Management. (In Press).

Ustin S., DiPietro D., Underwood S., and K. Olmstead. 2001: Hyperspectral remote sensing for invasive species detection and mapping.. Abstracts of Papers American Chemical Society 221:AGRO 34.

Van Aardt Jan. 2000: Spectral Seperability among Six Southern Tree Species. PhD thesis. Virginia Polytechnic Institute and State University, Blacksburg VA.

Van der Pas, J. B.; Kimberley, M. O.; Kershaw, D. J. 1984: Evaluation of the assessment of Dothistroma needle blight in stands of *Pinus radiata*. New Zealand Journal of Forestry Science 14(1): 3-13.

Vrindts E. and J. De Baerdemaeker. 1999: Optical weed detection and Evaluation using Reflection Measurements. SPIE 3542: 279-289.

Westman W. and C. Price. 1988: Detecting air pollution stress in southern California vegetation using Landsat Thematic Mapper band data. Photogrammetric Engineering and Remote Sensing 54 1305-1311.

Appendix: Satellite and Aerial Remote Sensing Systems (from http://www.es.ucsc.edu/~hyperwww/chevron/instruments.html)

Instrument	Class & Platform	Owner/Agency	Instrument Specifics	Primary Uses	Positive-Negative Aspects
Advanced **E**arth **O**bserving **S**atellite ***(ADEOS)***	Multispectral satellite-borne	managed by National Space Development Agency of Japan (NASDA)	several instrument packages on board; see AVNIR, TOMS, OCTS, and POLDER	environmental assessment and study	ADEOS only acquired data from 1996-1997 due to broken solar panels ADEOS II is planned to replace ADEOS I
Advanced **L**and **I**mager ***(ALI)***	Multispectral, Panchromatic flown aboard EO-1	NASA	**Multispectral** 10 bands 0.4-2.4 um 30m pixel 37km swath width **Panchromatic** 10m pixel	designed to produce images directly comparable to Landsat 7 ETM+, will establish data continuity with previous Landsats	finer resolutions than available on Landsat, though it's sister instrument Hyperion has far superior spectral resolution vastly increased SNR over Landsat 7
AIRborne **S**ynthetic **A**perature **R**adar ***(AIRSAR)***	Radar airborne - DC8	operated by NASA	**P, L, C bands** interferometric with L and C slant range resolution of 10m azimuth resolution of 1m ground swath 10-15km runs in several modes including high resolution 80MHz SAR, TOPSAR (data coregistered with DEMs, ATI mode (C and L bands along track)	production of very high resolution DEM's, ground movement quantification	though DEMs produced are quite good, there can be systematic height errors no systematic repeat coverage as it is flown on aircraft PACRIMII acquistions collected data on many underepresented Pacific Rim countries including Indonesia and Papua New Guinea

Australian **R**esource **I**nformation and **E**nvironmental **S**atellite ***(ARIES)***	Hyperspectral and Panchromatic satellite-borne	adminstered by CSIRO, Auspace Ltd., and ACRES	**~32 bands** 0.40-1.05um 20 nm bandwidth **~32 bands** 2.00-2.50um 16 nm bandwidth **1 band** Panchromatic 10m pixel 30m pixel 15km swath width 7 day revisit	mineralogical and vegetation mapping	one of the first planned hyperspectral satellites launch has been pushed back to 2004
Advanced **S**paceborne **T**hermal **E**mission and **R**eflection Radiometer ***(ASTER)***	Multispectral Terra satellite	NASA (Japan/U.S./Australia)	**3 bands** 0.52-0.86um 15m pixel **6 bands** 1.60-2.45um 30m pixel **5 bands** 8.125-11.65um 90m pixel stereo capability 60km swath width 16 day revisit	vegetation change natural hazard short term climate change coral reef degradation resource exploration high resolution DEM cloud free map of planet	one of only a few multi-band thermal satellite instrument capability for on-demand data acquistion requests
Advanced **V**ery **H**igh **R**esolution **R**adiometer ***(AVHRR)***	Multispectral carried on POES Polar Orbiting Environmental Satellite	NOAA	**5 bands** 0.58-12.50um (varying bandwidths) 1.1km pixel 2700km swath width daily images	vegetation distribution and seasonal changes on continent scales	good for large scale vegetation/ecosystem studies, but spatial and spectral resolution is poor for identification of communities/species

Advanced **V**isible/ **I**nfra-**R**ed **I**maging **S**pectrometer ***(AVIRIS)***	Hyperspectral flown on the NASA ER-2 at 20km	NASA-JPL	**224 bands**(10nm wide) 0.40-2.50um 20m pixel 11.5km swath width	ecology, oceanography, geology, snow hydrology, cloud and atmosphere studies	very good calibration and SNR must be an AVIRIS/NASA PI to get overflights, otherwise very expensive 20m pixels make vegetation studies more difficult, but excellent for mineral/rock work
Compact **A**irborne/ **S**pectrographic **I**mager ***(CASI)***	Multispectral/Hyperspectral flown on aircraft of choice	manufactured by Itres Research Ltd. (see website for companies that own these)	**variable bands (~19-288)** (~2-12nm wide) 0.40-1.0um 1.2m pixel/1km altitude variable swath width	ecology, geology, coastal zones, agriculture, environmental monitoring, etc.	user selection of either *spatial mode* which allows for particular band center selection (usually non-contiguous) or *hyperspectral* mode which allows for contiguous band collection only images in the VIS/NIR no data collected in the SWIR hence geology applications are limited collection all the way down to 400nm makes this instrument a good option for aquatic studies though this collection reduces overall SNR

Coastal **Z**one **C**olor **S**canner ***(CZCS)***	Multispectral Environmental satellite flown onboard Nimbus-7 from 1978-1986	NASA	**6 bands** 0.43-0.68um 20nm bandwidth **1 band** 0.70-0.80um **1 band** 10.5-12.5um	ocean color surveillance measure concentrations of chlorophyll-a map bioproductive regions map suspended sediment detect pollutants map temperatures of waters	excellent global coverage, but poor spatial resolution no longer collecting imagery(its successor is ***SeaWiFS***)
Defense **M**eteorological **S**atellite **P**rogram ***(DMSP)***	Multispectral Environmental satellite	NOAA, NGDC, DoD	**2 telescopes** 0.40-1.10um 10.0-13.4um 0.55km spatial resolution **1 photomultiplier tube** 0.47-0.95um 2.7km spatial resolution whiskbroom scanner	aurora and cloud imaging fire and city lights imaging	excellent global coverage, night time imaging poor spatial resolution
Earth **O**bserving-**1** ***(EO-1)***	Multispectral and Hyperspectral satellite-borne	NASA	three instruments onboard; see ***Hyperion, ALI,*** AC	imaging of land ecosystems provides continuity of imaging with Landsat-7 ETM+	collection of data concurrent with Landsat-7 ensures robustness of experimental data first hyperspectral satellite to be launched **launch expected November 2000**

European **R**emote Sensing **S**atellite- **1,2** ***(ERS-1,2)***	Radar/Multispectral satellite-borne	ESA (European Space Agency)	**1 band** C-band Radar **6 bands** 3 Visible 1 Near Infrared 3 Thermal Radar - 100km swath width Multispectral-180-500km swath width	used to image polar regions, coastal zones, oceans, and land successful mapping and identification of oil spills, floods, tectonic movements, climate events, ocean floor topography, sea surface temperature, etc.	SAR operates in all weather and in the dark its abilities to map geology are limited, but vegetation and vegetation health may be studied and mapped One of only two satellite-borne radar systems
Geostationary **O**perational **E**nvironmental **S**atellites ***(GOES)***	Multispectral Environmental satellites	NOAA	**1 band** 0.55-0.70um 1km pixel resampled to 8km **1 band** 10.50-12.60um 8km pixel hemisphere scale images	primarily used for meteorologic studies	two juxtaposed satellites allow for total earth imaging every day low spatial resolution doesn't allow for earth resource studies
Hyperion	Hyperspectral onboard the EO-1 satellite	NASA	**220 bands** 0.40-2.50um 10nm bandwidth 30m pixel 7.5km swath width	general earth materials mapping geology, mining, forestry, agriculture, and environmental management	the large number of bands allows for identification of materials, however the large pixel size may hinder vegetation studies in particular mission life is only set for 2 years launch date Nov 2000

Hyperspectral **Map**per ***(HyMap)*** (also ***Probe-1*** owned by Earth Search Sciences, Idaho, USA)	Hyperspectral flown on small aircraft at low altitudes	HyVista Inc., Sydney, Australia	**128 bands** 0.44-2.50um 15nm bandwidth 2-10m pixels 1-5km swath widths	geological and biological mapping ecology studies oceanography resource mapping and exploration	high SNR (>1000:1) ability to fly on-demand acquistions high spatial resolutions available frequent repeat imaging is expensive
Ikonos-1	Panchromatic and Multispectral satellite-borne	Space Imaging, Inc., Thornton, CO, USA	**1 band** Panchromatic 1m pixel **Multispectral** 4m pixel	agriculture urban planning emergency response media mapping land use environmental monitoring mining & exploration	highest spatial resolution available from a satellite expensive provides ability to "sharpen" low resolution images from other sensors

India **R**emote **S**ensing satellites ***(IRS)***	Multispectral and Panchromatic four separate satellites launched between 1988 and 1997	National Remote Sensing Agency, India (imagery also available from EOSAT, U.S.A.)	IRS satellites carry three different versions of the LISS (linear imaging self-scanning) instrument: **LISS I** 4 bands 0.45-0.86um 72.5m pixel 148km swath width **LISS II** 4 bands 0.45-0.86um 36.3m pixel 146km swath width **LISS III** 4 bands 0.52-1.70um 23.5m-70.5m pixel 141km swath width 1 panchromatic band 0.50-0.75um 5.8m pixel 70km swath width	classic earth resource satellite used for geology, vegetation, agriculture, oceanography, resource exploration and management, environmental monitoring and study	large pixel sizes make ecosystem studies more difficult, however the PAN band on the LISS III allows for sharpening of the imagery
Japanese **E**arth **R**esources **S**atellite ***(JERS-1)***	Multispectral and Radar satellite-borne (launched in 1992)	National Space Development Agency (NASDA)-Japan (data also obtained by NASA)	**Optical Sensor (OPS) system** 7 bands 0.52-2.40um 20m pixel 75km swath width images in stereo can also be produced by the OPS system	Earth resource satellite environmental protection, agriculture, forestry, fishery, land use, disaster prevention, coastal monitoring	the inclusion of the SWIR wavelength region allows for identification of minerals, however, blurring and striping in the OPS imagery renders the imagery unusable for many applications no successor to JERS-1 has been announced end of mission in 1998

Landsat 1-7	Multispectral and Panchromatic seven satellites have been launched since 1972: **Landsat1** 1972-1978 MSS **Landsat2** 1975-1982 MSS **Landsat3** 1978-1983 MSS **Landsat4** 1982-1987 MSS,TM **Landsat5** 1985-present MSS,TM **Landsat6** 1993 lost at launch **Landsat7** 1999-present ETM+	NASA	**Multi-Spectral Scanner (MSS)** 4 bands 0.5-1.1um 80m pixel 185km swath width revisit 16-18 days **Thematic Mapper (TM)** 7 bands 0.45-12.50um 30m pixel (VIS/NIR/SWIR) 120m pixel (TIR) 185km swath width revisit 16 days **Enhanced Thematic Mapper+ (ETM+)** 7 bands 0.45-12.5um 30m pixel (VIS/NIR/SWIR) 60m pixel (TIR) 1 PAN band 0.52-0.90um 15m pixel 183km swath width revisit 16 days	classic earth resource satellite geology, oceanography, agriculture, environmental monitoring, hazard prevention, mining, land use and degradation, snow studies, deforestation, coastal use and degradation	the continuity of the Landsat program is an invaluable resource; it allows a continuous study of our Earth since 1972 inclusion of a PAN band in Landsat7 will allow for studies that require a finer spatial resolution, such as vegetation studies in general, the 30m spatial resolution makes fine scale ecosystem studies difficult
Modis **ASTER** airborne simulator ***(MASTER)***	Multispectral flown in a Beachcraft B200 NASA ER-2 NASA DC-8	JPL/NASA	**50 bands** 0.40-13.0um 5-50m pixel (depending on flight height)	geology, ecology, oceanography	provides validation for EO-1 sensors, MODIS and ASTER inclusion of the thermal bands allows for multi-purpose studies that usually require several instruments flown only by request which is not guarenteed browsable archive of imagery online

Multi-angle **I**maging **S**pectro**R**adiomet er *(MISR)*	Multispectral onboard the Terra satellite	JPL/NASA	**4 bands** 0.45-0.87um 250-275m pixel (depending on viewing angle) 360km swath width revisit 2-9 days	enhanced study of earth climate study of different atmospheric particles, cloud forms, and land surface covers very accurate estimates of total amount of sunlight reflected from Earth	though MISR only has four bands, it's strength lies in it's nine widely spaced viewing angles which allow scientists to conduct studies not possible before
Multispectral **I**nfrared and **V**isible **I**maging **S**pectrometer *(MIVIS)*	Hyperspectral airborne	acquired by CNR (Italian National Research Council) in framework of LARA (Airborne Laboratory for Environmental Studies	**102 bands** VIS 0.43-0.83um (20 channels) NIR 1.15-1.55um (8 channels) SWIR 1.983-2.478um (64 channels) TIR 8.18-12.7um (10 channels) IFOV 2.0mrad variable pixel size	monitoring of active volcanoes, coastlines, lagoons, oceans, farming interests, oil slicks, general waste discharges, archeological sites	though not truely hyperspectral, its spectral range is unique in that it covers not only VIS/IR, but also a portion of the TIR all in the same sensor repeat coverage costly operated primarily for Italian interests
Moderate-Resolution **I**maging **S**pectroradiomete r *(MODIS)*	Multispectral onboard the Terra satellite	JPL/NASA	**36 bands** 0.400-15.0um 1km pixel 2330km swath width revisit 1-2 days	earth resource satellite land cover, vegetation cover, fire and thermal anomalies, snow and ice cover, oceanography	by including a moderate number of bands, mineral and plant identification now becomes an approachable problem a 1 km pixel is quite large and there will be a lot of pixel mixing from this

Naval **E**arth **M**ap **O**bserver ***(NEMO)***	Hyperspectral, Panchromatic satellite launch delayed indefinitely	Office of Naval Research(ONR) Naval Research Laboratory(NRL)	**Coastal Ocean Imaging Spectrometer (COIS)** 220 bands 10nm bands 0.4-2.4um 30-60m pixel 30km swath width 7 day revisit **Panchromatic Imager** 0.45-0.67um 5m pixel	characterization of world littoral regions demonstrate automated, on-board processing, analysis, and feature extraction study of water clarity, bathymetry, underwater hazards, currents, oil slicks, bottom type, tides, bioluminescence potential, beach characterization, atmospheric water vapor, subvisible cirrus	mapping terrestrial and aquatic materials in support of military operations, though commercial applications are also planned inclusion of the ORASIS (Optical Real-Time Spectral Identification) may make the volumnious data amounts managable, though the accuracies will likely be lower financial issues appear to have shelved the launch indefinately
Orbview-4 (Warfighter)	Hyperspectral, Multispectral and Panchromatic satellite-borne launch set for 2001	Orbital Science Corporation Army,Navy,Airforce, NASA	**Multispectral** 4 bands VIS/NIR 4m pixel 8km swath width **Hyperspectral** 200 bands 0.4-2.5um 8m pixel 5km swath width **Panchromatic** 1 band in VIS 1m pixel 8km swath width revisit 2-3 days	environmental impact statements infrastructure planning urban planning crop health assessment/vegetation studies resource exploration geology habitat monitoring mission planning for national security and surveillance	the high spatial resolution hyperspectral spectrometer is an unprecedented addition to the constellation of satellites, however the U.S. government is balking at releasing such spatial information to the public a very large amount of data as files are so large
Probe-1	see ***HyMap***				

Radarsat	Radar satellite-borne	Canadian Space Agency (CSA) Canadian Center for Remote Sensing (CCRS) distributed by Radarsat International	**C-band** single frequency 5.7cm variety of beam selections 10-100m pixel resolution 35-500km swath width variable revisit times approx. 6 days at mid-latitudes	monitor environmental change support resource sustainability monitor sea-ice conditions geology (structural interpretation especially)	a big plus to radar is it's ability to see through clouds; this is important for work done in tropical regions radar is also strongly scattered by vegetation this system has a polar orbit, so it sees more of the earth than the earlier SIR-C mission
Spatially **E**nhanced **B**roadband **A**rray **S**pectrograph **S**ystem ***(SEABASS)***	Hyperspectral flown on DeHavilland Twin Otters	The Aerospace Corporation, CA, USA	3.0-5.4um, 7.8-13.6um 2-12.5ft pixel IFOV=1mrad	mineral exploration, possible hazard monitoring, environmental	one of the only commercially available instruments with hyperspectral thermal bands allows for identification of many silicate minerals not easily identified in the VIS/NIR/SWIR systematic repeat coverage not an economic reality for most flights are combined with groundtruth measurements
Sea-viewing **Wi**de **F**ield-of-View **S**ensor ***(SeaWiFS)***	Multispectral launched aboard the SeaStar satellite in 1997	NASA/Orbital Science Corp.	**8 bands** 0.40-0.89um 1.1km pixel 1502km swath width revisit 1 day	designed to monitor ocean physics, chemistry, and biology provide quantitative data on global ocean bio-optical properties an ocean color sensor to replace the now defunct CZCS	rapid repeat time allows for excellent multi-temporal studies, however the large pixel size and small number of bands rules out a lot of terrestrial studies---this is an ocean sensor

Shuttle **R**adar **T**opography **M**ission ***(SRTM)***	Radar carried aboard the Space Shuttle Endeavour	NASA, NIMA, DLR (Germany), ASI (Italy)	**C and X Band** 30m spatial sampling 16m absolute vert. height accuracy 10m relative vertical height accuracy	to use C and X band interferometric SAR to acquire topographic data over 80% of Earth's land mass (between 60degN and 56degS) during an eleven day mission geology, earthquake research, volcano monitoring, hydrologic modeling, co-reg of other remote sensing data, civil engineering, land use planning, line of site determinations, flight simulators, various military applications	only a one-time 11 day mission, thus baselining is prime objective allows for draping of other remotely sensed imagery to add a third dimension to image analysis and interpretation
Spaceborne **I**maging **R**adar**-C**/ **X**-band **S**ynthetic **A**perature **R**adar ***(SIR-C/XSAR)***	Radar carried in 1994 on two separate flights of the Space Shuttle Endeavour	NASA, DLR(Germany), DARA(Italian)	**SIR-C** L and C band radar **XSAR** X band 15-90 km swath width 10-200 m spatial resolution	part of NASA's Mission to Planet Earth with a focus on climate change mapping of vegetation coverage, snow pack extent, wetlands, rock type and distribution, volcanic activity, ocean wave heights, wind speed, etc.	The first radar instrument to send and receive two bands weather and light conditions not an issue global coverage and multitemporal data shuttle borne, so no more data available from this mission

Systeme **P**robatoire d'**O**bservation de la **T**erre ***(SPOT)***	Multispectral and Panchromatic four satellites launched from 1986-1998, SPOT5 proposed launch in 2001	designed by Centre National d'Etudes Spatiales (CNES),(France,Belgium,Sweden)	**SPOT XS** 3 bands 0.50-0.89um 20m pixel 60km swath width **SPOT Pan** 1 band 0.51-0.73um 10m pixel 60km swath width	earth resource satellite cartography, agriculture, environmental monitoring, landuse, landcover, geology, exploration, etc.	the rapid repeat time and stereo capability give this satellite something many of the others don't have only three bands in the VIS/NIR however, limits it's use in sophisticated landcover mapping