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Mapping of Scotch Broom (*Cytisus scoparius*) with Landsat Imagery

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Methods were developed and tested for mapping the distribution of Scotch broom, an invasive shrub species expanding its range and disrupting native species and habitats in several parts of the world. During spring, the Scotch broom produces yellow flowers. Landsat imagery during the flower bloom period and during summer was acquired for several years for a study area on Vancouver Island, British Columbia, Canada. Ground-based reflectance measurements plus statistical separability tests were conducted to determine the effectiveness for identifying Scotch broom with Landsat spectral bands, band ratios, vegetation indices, and combinations of bloom and nonbloom imagery. Maximum likelihood classifications of three Scotch broom density classes (dense, $\geq$ 75% cover; moderate, 25 to 75%; low, 10 to 25%) and other land covers were run with various image and band sets and tested against independent reference sites. Accuracies of classifications using the better band combinations for moderate and dense Scotch broom patches combined were on the order of 80%, with unreliable results for sites of low Scotch broom density. Scotch broom patches less than 0.5 ha were often missed. Some commission error occurred (areas erroneously classified as Scotch broom). Suggested improvements are the use of time series of classifications over multiple years, incorporating knowledge of Scotch broom spread mechanisms or temperature and elevation limitations, and use of higher resolution satellites if the expense warrants it. Despite some limitations, a satellite-based remote sensing approach may be useful for aspects of Scotch broom management.

Nomenclature: Scotch broom, *Cytisus scoparius* (L.) Link.
Key words: Accuracy assessment, flowering, monitoring, remote sensing, spectral bands.

Se desarrollaron y evaluaron métodos para mapear la distribución de *Cytisus scoparius*, una especie invasivas de arbusto que está expandiendo su área de influencia y está perturbando especies nativas y hábitats en varias partes del mundo. Durante la primavera, *C. scofparius* produce flores amarillas. Imágenes Landsat durante el período de floración y durante el verano fueron adquiridas durante varios años para un área de estudio en la isla de Vancouver, British Columbia, Canada. Mediciones terrestres de reflectancia más pruebas estadísticas de separabilidad fueron realizadas para determinar la efectividad de identificar *C. scoparius* con bandas espectrales Landsat, ratios de bandas, índices de vegetación, y combinaciones de imágenes con y sin floración. Clasificaciones de probabilidad máxima de tres clases de densidad de *C. scoparius* (densa, $\geq$ 75% de cobertura; moderada, 25 a 75%; baja, 10 a 25%) y otras coberturas del terreno fueron analizadas con varias imágenes y sets de bandas y evaluadas contra sitios de referencia independientes. La exactitud de las clasificaciones usando las mejores combinaciones de bandas para combinados de parches de *C. scoparius* moderados y densos estuvieron en el orden de 80%, con resultados no confiables para sitios con densidades bajas de *C. scoparius.* Los parches de *C. scoparius* de menos de 0.5 ha frecuentemente no fueron identificados. Ocurrieron algunos errores de asignación (áreas erróneamente clasificadas como *C. scoparius*). Las mejoras sugeridas son el uso de series temporales de clasificaciones a lo largo de múltiples años, incorporando el conocimiento de los mecanismos de dispersión de *C. scoparius* o limitaciones de temperatura o elevación, y el uso de satélites de alta resolución, si el costo lo amerita. A pesar de algunas limitaciones, un sistema remoto basado en imágenes satelitales podría ser útil para aspectos de manejo de *C. scoparius.*

Many species of plants have been introduced to nonnative environments for beneficial purposes, but some of these exotics have escaped, invaded, and expanded their ranges into the new environment beyond usefulness. Effects can range from local to continental. Incursion of such invasive plant species poses significant threats to global biodiversity and ecosystem functioning (Mooney and Cleland 2001), and anthropogenic disturbances such as land conversion, grazing, and habitat fragmentation combined with international trade and climate change are likely to exacerbate this problem. Thus, the challenge to land managers is how to manage nonnative plants effectively to preserve the native biodiversity. An essential element of this is to know how to delineate the spatial extent of invasive

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species to ascertain the severity or intensity of invasion. Remote sensing offers a potential flexible tool for helping to monitor and manage invasive weeds.

Remote sensing has been used to map invasive weed species using varying spatial resolutions from satellite and airborne sensors (e.g., Anderson et al. 1993; Arnold et al. 1985; Casady et al. 2005; Everitt et al. 2001; Lass et al. 2005; Odom et al. 2003; Peters et al. 1992; Ullah et al. 1989; Underwood et al. 2003). A variety of techniques have been used. Some applied standard remote sensing methods, whereas others were specifically tailored to the invasive species and its setting. According to Lamb and Brown (2001), the primary requirements to detect and map weeds successfully using remote sensing are that (1) suitable differences in spectral reflectance or texture exist between weeds and their background soil or plant canopy and (2) the remote sensing instrument has appropriate spatial and spectral resolution to detect the presence of weed plants.

Scotch broom is an alien ornamental plant that has been introduced and become a problem invasive species in several parts of the world. It is a native of southern Europe (Spain and Portugal) and northern Africa. It has been found in India, Sri Lanka, Australia, New Zealand, South Africa, Chile, Brazil, and Columbia, as well as in other Latin American countries, and beyond its native range in southern Europe (Prasad 2005; Zouhar 2005). In North America it has been introduced and spread on both the east and west coasts of the United States and Canada. The incursion and spread in British

Figure 1. Invasive Alien Plant Program map of Scotch broom distribution in British Columbia Ministry of Forests, Lands, and Natural Resource Operations (IAPP 2014). Red dots are reported occurrences of Scotch broom.

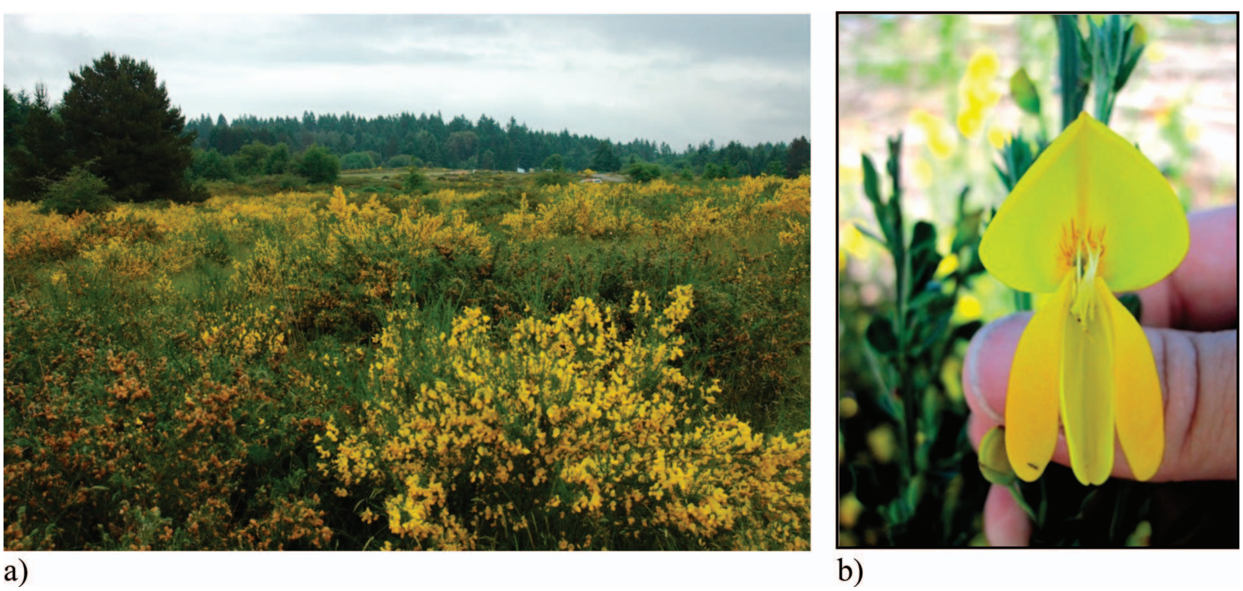

Figure 2. (a) Scotch broom plant. (b) Flower and leaves.

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Columbia (Figure 1), and in particular Vancouver Island (Peterson and Prasad 1998; Zielke et al. 1992), is the target of this study, although it is expected that the methods developed and results can be helpful for adaptation to cases elsewhere in the world and perhaps for some other invasive weed species with similar biological features and spread mechanisms.

Of particular concern in northwestern North America is the threat to unique, endangered Garry oak (*Quercus garryana* Dougl.) ecosystems and other native plants in British Columbia and the Pacific Northwest (Oregon, Washington, California). Together with another related invasive weed, gorse (*Ulex europaeus* L.), Scotch broom has become a nuisance weed, limiting grazing, recreation facilities, and timber production (Prasad 2000). It is a very aggressive invasive weed that in northwestern North America has no natural parasites or predators to check its spread (Prasad 2002). Scotch broom is also adaptable to varying ecological conditions and can grow on dry, poor soils and outcompete other vegetation because of its nitrogen-fixing capability (Hosking et al. 1996; Prasad 2000; Zouhar 2005). Once established it is very difficult to eradicate because of its high seed production and ability to grow from any remaining shoots if cut. The most effective method is uprooting, which is expensive and time consuming (Huckins and Soll 2004; Prasad 2000). A recent growing issue is that the concentration of biomass and, particularly, volatile oils in Scotch broom and gorse poses a fire hazard (Clements et al. 2001). Thus a site-specific map showing concentrations of Scotch broom is important to municipal fire departments and provincial or state fire control agencies. Currently in British Columbia there is a poor understanding of its distribution, rate of spread, locations of new incursions, and overall extent of the problem. It would be extremely useful to have a method to map the location of Scotch broom efficiently, provide an indication of its density (e.g., proportion of cover), and monitor it over time.

Biological Considerations. Scotch broom is a perennial with woody stem and branches (Figure 2) that can occur in dense and low-density patches and as a monoculture or intermixed with other vegetation (Figure 3). It has dark green tri-foliate elongated leaves 4 to 8 mm long that occur in moderate density, evenly distributed along the branches. Most leaves remain on the branches throughout the year. The plant generally grows to from 1 to 4 m in height, and on Vancouver Island its height is typically between 1.5 and 2.5 m. It has a life span of 10 to 25 yr (Peterson and Prasad 1998; Zouhar 2005).

Scotch broom is spread locally by its seeds falling near the plant. It is a prolific seed producer (18,000 plant^{-1}), half of which survive in soils as seed banks for more than 35 yr. Seeds are in pods; pod bursts can be explosive and scatter the seeds to a distance on the order of 1 m, but sometimes as far as 2 to 4 m (Bossard 1991; Peterson and Prasad 1998; Zouhar 2005). Therefore, a new outbreak tends to start with a few plants but grows to dense patches, usually overpowering the other vegetation. Thus it normally occurs in dense patches ranging from 10 to 100 m or much greater. Often the patches become monocultures. Normally it takes 5 to 10 yr to build up patches and colonies of thickets. It is generally only in early stages of establishment that low-density situations occur. Because the main means of long-distance transport is through seeds attached to vehicles, logging or construction equipment, and seed-contaminated gravel (Boateng 1994), new incursions can show up in isolated pockets far from existing occurrences; thus, if these are to be detected, a wide search area is needed and techniques requiring expensive high-resolution imagery or specialized sensors are less desirable. Broom is expected to occur in target settings such as roadsides, power lines, clearcuts, and construction sites, and Scotch broom distribution can be limited by elevation (Perry et al. 1979) and cold winter temperatures (Peterson and Prasad 1998).

Scotch broom is shade intolerant and will not grow in areas of high shade (DiTomaso 1998). It is often an early seral colonizer (Hosking et al. 1996) and will establish in areas of recent soil disturbance, such as forest harvest (Parsons and Cuthbertson 1992). As native species re-establish or the forest canopy closes, Scotch broom can be shaded out and will only continue to compete with other species if under an open tree canopy (Peterson and Prasad 1998). Thus, an advantage for detecting Scotch broom with remote sensing is that most occurrences might be in the open and visible to remote sensing sensors, and remote sensing techniques will generally not be confused by presence of tree overstory or even scattered trees.

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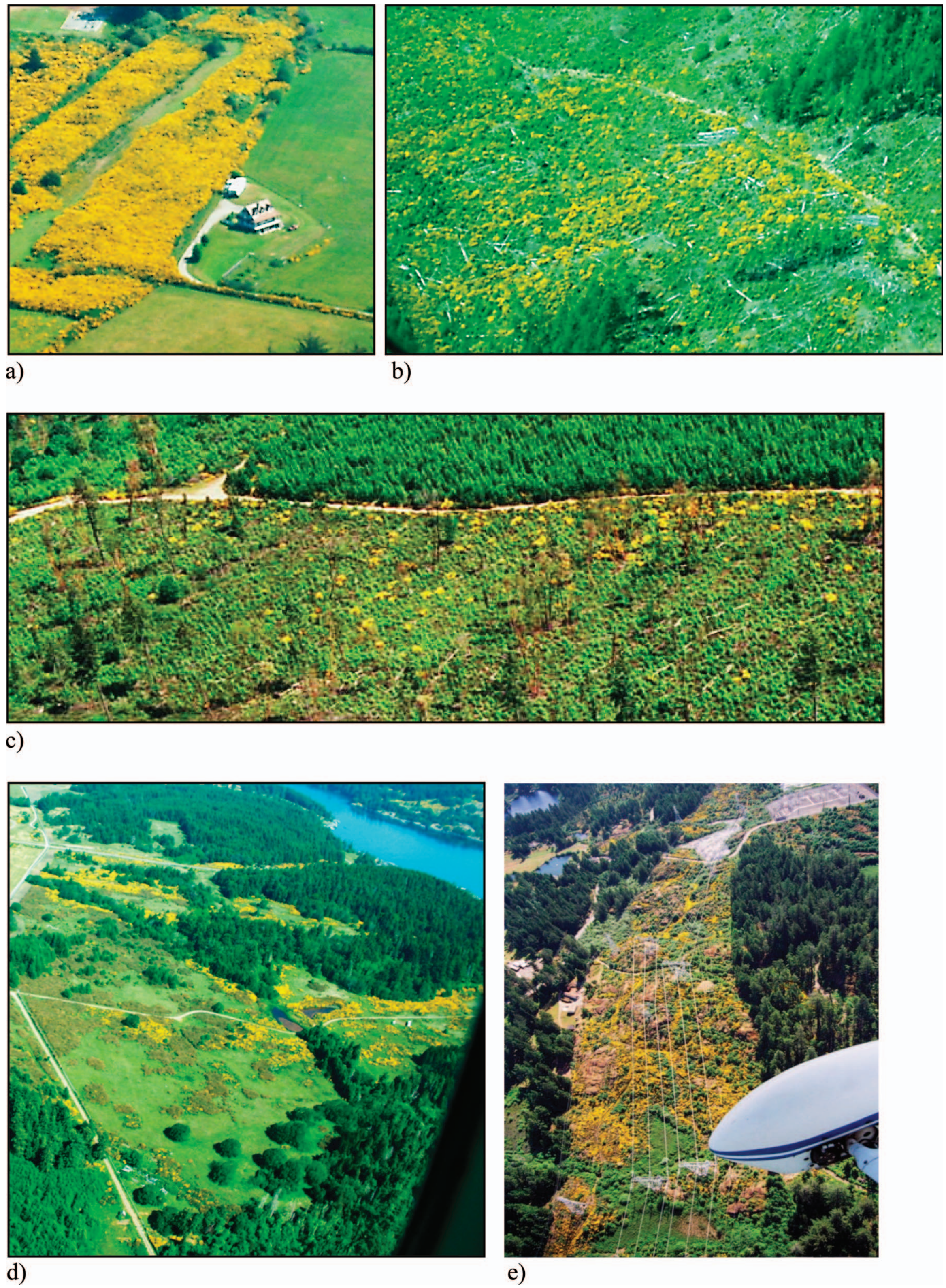

Figure 3. Scotch broom under flowering conditions. Photographs from June 4, 2003, aerial observation mission. (a) Dense Scotch broom, (b) moderate-density Scotch broom, (c) low-density Scotch broom, (d) mixture of patches of dense through low-density Scotch broom, (e) Scotch broom mixed with shrub, ground vegetation, and some bare rock and soil.

The biological cycle of Scotch broom can be used to advantage in a remote sensing approach. A possible technique is to utilize the flowering of Scotch broom; for a period in the spring the plants have abundant yellow flowers, and the plant and Scotch broom patches have a yellow color (Figure 2). The flowering period is normally 30 to 40 d. On Vancouver Island, flowering can begin in February (Peterson and Prasad 1998) but typically occurs from May to June. The longevity of the flowering period can be shortened by the effects of wind, rain, temperature, and grazing by insects during pollination. Another factor if one is surveying Scotch broom over a large area or perhaps even locally is the variability of the onset of flowering and dropping of flowers. For example, if the onset is different by 10 d across a region and the period of flowering is 30 d, then only for 20 d can one assume that all the Scotch broom throughout the region will be yellow and that a system based on detection of yellow will not miss areas of Scotch broom. Alternatively, if a local wind or rain storm causes premature loss of flowers, this would also result in omissions by a mapping system based on yellow coloration. Onset of flowering is mostly based on temperature and day length (photoperiod). On Vancouver Island, day length will not cause variation, but temperature gradients based on elevation or local setting could affect onset of flowering. Observations by the authors are that this is not a major factor within the region of this study, and onset is generally within a week or 10 d of each other. Onset of flowering is also mitigated by staging somewhat over time on an individual plant and among plants in a given patch.

Overview. This paper explores possible approaches to mapping locations of Scotch broom concentrations suitable for application on a regional basis. Medium resolution satellite imagery is most appropriate because it has broad coverage and is inexpensive. Landsat Thematic Mapper imagery was used in this study. An analysis was conducted to select the best band combinations, to explore band ratios and indices that might highlight the yellow coloration, and to estimate the likely effectiveness of other sensors with only visible and near-infrared spectral bands. The overall goal was to develop a method that will permit mapping of the location of Scotch broom occurrences and provide useful information to land managers, policy makers, fire control agencies, foresters, and those monitoring the movement and severity of invasive species.

Materials and Methods

Study Site. The study site was located in southern Vancouver Island, British Columbia (Figure 4), the region of the most serious incursion of Scotch broom on Vancouver Island. It is in the Pacific Maritime ecozone (Wiken 1986) and has a sub-Mediterranean climate. Elevation ranges from sea level to approximately 1,000 m, and relief varies from low through rolling to mountainous. Several large cities (greater Victoria, population 350,000, and Nanaimo, population 84,000) and numerous smaller communities lie within the study area and contain urban, suburban, commercial, and light industrial settings. Otherwise, land use is mainly forest with forest management activity and some agriculture and rural residential. Forest harvest is mainly clearcuts and some partial cuts. A characteristic of the eastern part of the study region is intermixtures of agriculture, forestry, rural residential, and urban/commercial/light industrial land use. Development and growth rates have been moderate but steady, as has forest harvest activity, resulting in construction sites, as well as forestry cuts and access trail or road construction and thus supplying a considerable number of disturbed sites and opportunities for transport of Scotch broom seeds and establishment of new colonies.

Image Data. Five Landsat images were obtained for this project (Table 1). Three June images (2000, 2002, 2003) acquired while the Scotch broom plants were just past their peak bloom period were selected for use in this study. The July images (2000, 2003) were acquired during the summer period when the Scotch broom had finished blooming and the current year's new branches had attained a mature green coloration. Because of cloud cover and haze, the June 19, 2000, data were omitted from use in automated classification; nevertheless, it was useful in demonstrating that, at least visually, the yellow flowering of the Scotch broom was detectable using Landsat imagery. All Landsat images were processed to top of atmosphere (TOA) reflectance (Teillet 2005) (i.e., image values were converted to radiance and adjusted for sun position but not corrected for atmospheric effects such as scattering). After TOA correction, images

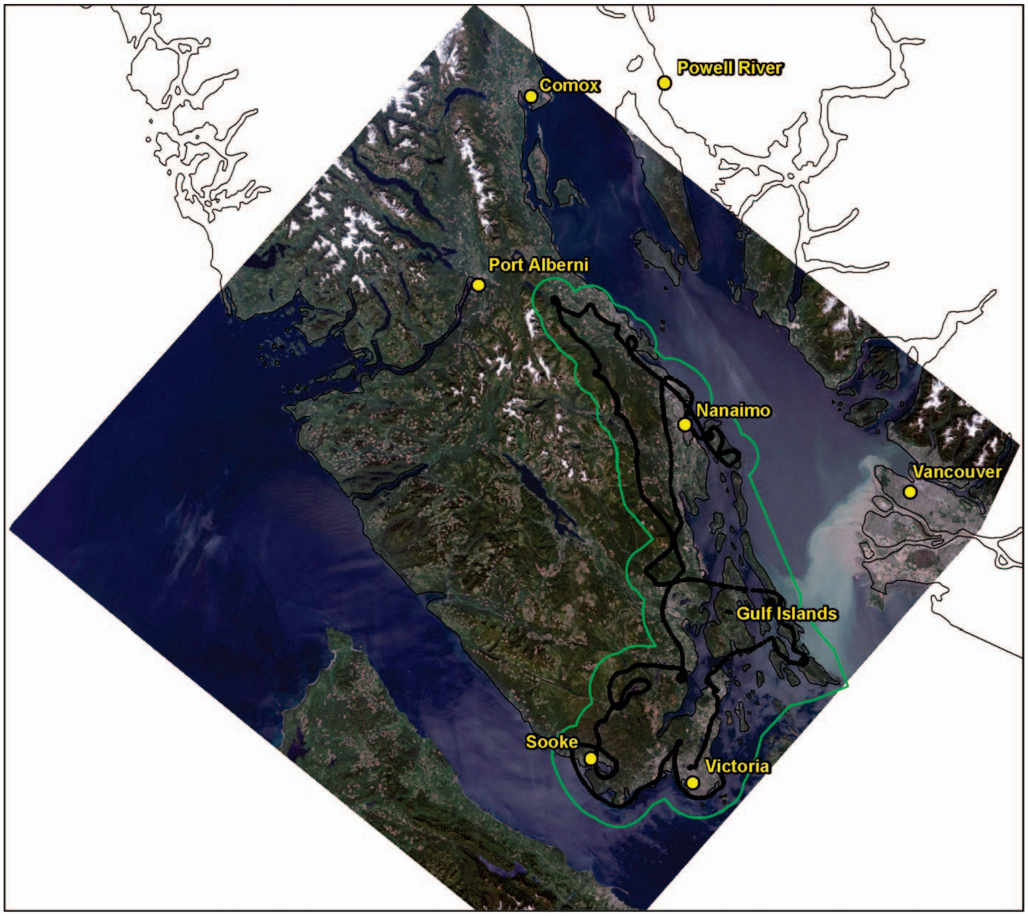

Figure 4. Study site, southern Vancouver Island, British Columbia (green outline). June 4, 2003, Landsat 5 image (bands 3, 2, and 1 displayed as red, green, blue). Coincident June 4 aerial survey track (black line).

were ortho-corrected with nearest neighbor resampling to 25-m resolution. Additionally, images were radiometrically normalized among each other using the technique of Joyce and Olsson (1999). This process applied a gain and offset to pixel values of each spectral band of each image such that the image values for the range of land cover types over the study area were similar to those of a selected baseline image—in the case of this study, the data of June 9, 2002. Figure 5 shows a normal color rendering of a subarea of the test area for a summer image and two images during bloom.

Table 1. Landsat images.

Satellite	Date	Image path/row	Bloom period
Landsat 7	June 19, 2000	48/26	3 wk past peak bloom
Landsat 7	July 21, 2000	48/26	Summer, no bloom
Landsat 7	June 9, 2002	48/26	2 wk past peak bloom
Landsat 5	June 4, 2003	48/26	2 wk past peak bloom
Landsat 5	July 22, 2003	48/26	Summer, no bloom

Reference Data on Scotch Broom Distribution. Reference areas of known Scotch broom are used to assess how well automated classification captures Scotch broom, both from a visual comparison and a formal pixel-based accuracy assessment. In addition to Scotch broom areas, test areas of other cover types were created to assess the classification.

The main source of reference data was from aerial observation and aerial oblique photography taken in two missions during bloom periods specifically designed to capture Scotch broom areas. Two flights in a light aircraft were undertaken. The first flight was June 5, 2001. The second was June 4, 2003, corresponding to the day of one of the Landsat acquisitions (Figure 4). Photographs were taken of areas with Scotch broom, areas susceptible to Scotch broom invasion (cut blocks and other soil disturbances), and cover types like bare soil, exposed rock

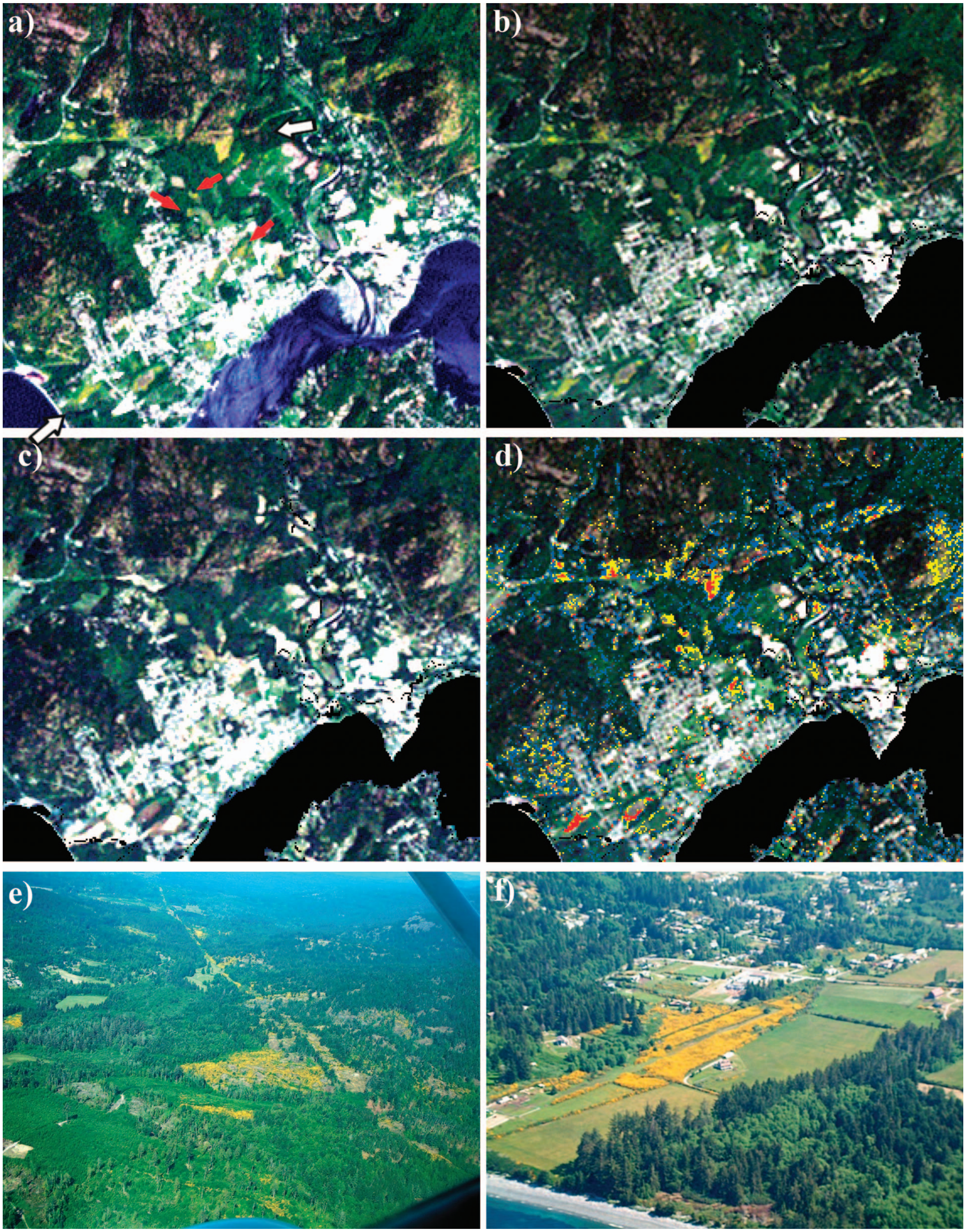

Figure 5. (a) June 2002 Landsat image; (b) June 2003 image; (c) July 2003 image; (d) June 2003 image with classification (2003 bloom/no-bloom with all six bands plus NDVI), Scotch broom dense is red, Scotch broom moderate is yellow, and Scotch broom low is blue; (e, f) 2003 oblique aerial photographs (see white arrows on panel (a) for location). Landsat images are normal color displays. Area is centered on Sooke and is 6.2 by 7.0 km. Red arrows on panel (a) point to example locations of Scotch broom.

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Table 2. Classes and class descriptions.[a]

Class	Description	No. of training sites	No. of test sites
Scotch broom dense	75–100% Scotch broom cover	23	23
Scotch broom moderate	25–75% Scotch broom cover	24	26
Scotch broom low	10–25% Scotch broom cover	18	17
Shrub	< 3m in height, mainly deciduous plants	5	5
Regeneration	Forest harvest areas with regenerating trees with heights above shrubs and grasses	12	13
RCC dense ground vegetation	RCC with dense > 75% ground vegetation cover	4	4
RCC moderate ground vegetation	RCC with 25–75% ground vegetation cover	6	7
RCC sparse ground vegetation	RCC with < 25% ground vegetation cover	9	10
RCC bare	RCC with exposed soils	9	10
Recent partial cut	Recent harvest with trees remaining (i.e., selective cutting or tree spacing)	6	7
Brown grass	Dry grass fields with yellow or brown coloration	4	5
Bare rock	Gravel quarries, natural rock areas	13	13
Bare soil	Tilled fields	4	4
Crop	Cropland including hay fields	7	8
Green grass	Green lawns, playing fields	9	9
Urban	Urban and industrial areas with little or no vegetation	7	8
Softwood	Conifer trees	12	11
Hardwood	Deciduous trees	4	5
Mixedwood	Mixed conifer and deciduous stands	6	5
Water	Lakes, rivers	11	11
Snow	Snow and ice	7	8
Gorse[b]	Gorse	—	—

[a] Abbreviation: RCC, recent clearcuts.

[b] Gorse is not used in the classifications.

outcrops, forest regeneration, shrub, grass, urban areas, and yellow flowering crops that might get confused with Scotch broom. The first flight acquired more than 300 photographs; any Scotch broom sites on the photography should still be Scotch broom in 2002 and 2003. Approximately 1,500 photographs were taken during the second mission. Both flights were flown at ca. 500 to 800 m above ground level. Scotch broom patches and other cover types were clearly visible and interpretable on the oblique photography, and notes taken during the flights provided further information. The tracks of both flights were transferred to a GIS to overlay on the Landsat imagery.

From these data, reference areas of known Scotch broom concentrations were outlined on the Landsat imagery. These areas were used for training the maximum likelihood classifier and for testing results. Three levels of Scotch broom concentration were defined (dense, 75 to 100% ground surface coverage; moderate, 25 to 75%; and low, 10 to 25%). For each site, the general mixture of cover type was noted (e.g., whether the Scotch broom was associated with bare ground, shrub, conifer regeneration, or herbs). A selection of sites were also outlined to represent other cover types in the landscape, especially those likely to be confused with Scotch broom.

Twenty-two classes of cover were identified (Table 2). Spectral characteristics for the reference areas were extracted; the mean value of all pixels in the reference area in each Landsat band was calculated (Figure 6). For the Scotch broom classes, the reference pixels were derived from 35 to 50 independent sites, each typically 4 to 45 pixels in size, with the dense Scotch broom sites often being smaller than the other Scotch broom sites. The other classes generally had a total of 275 to 1,200 pixels, with some like the softwood, regeneration, crop, and urban classes having 5,000 pixels and more. The reference areas were then split equally into two independent data sets: a "training" set and a "test" set (Table 2). The training set was used to derive statistics or spectral signatures (mean, standard deviation, and covariance matrices) for each class; these signatures were then used in a

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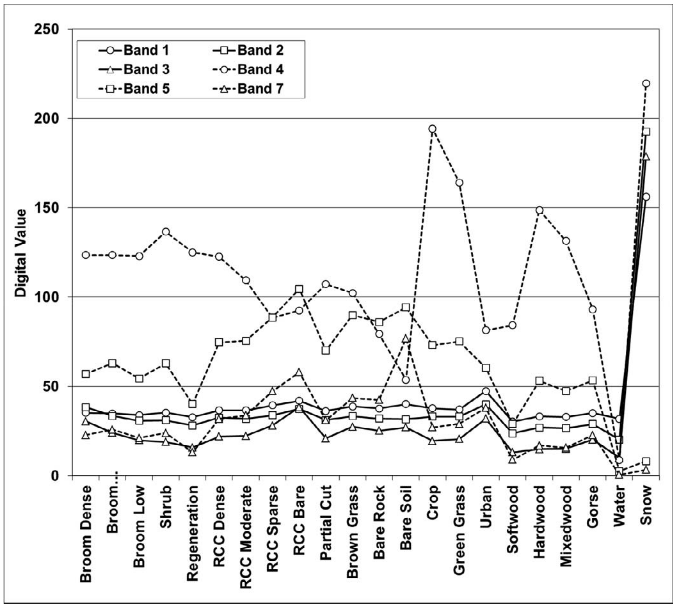
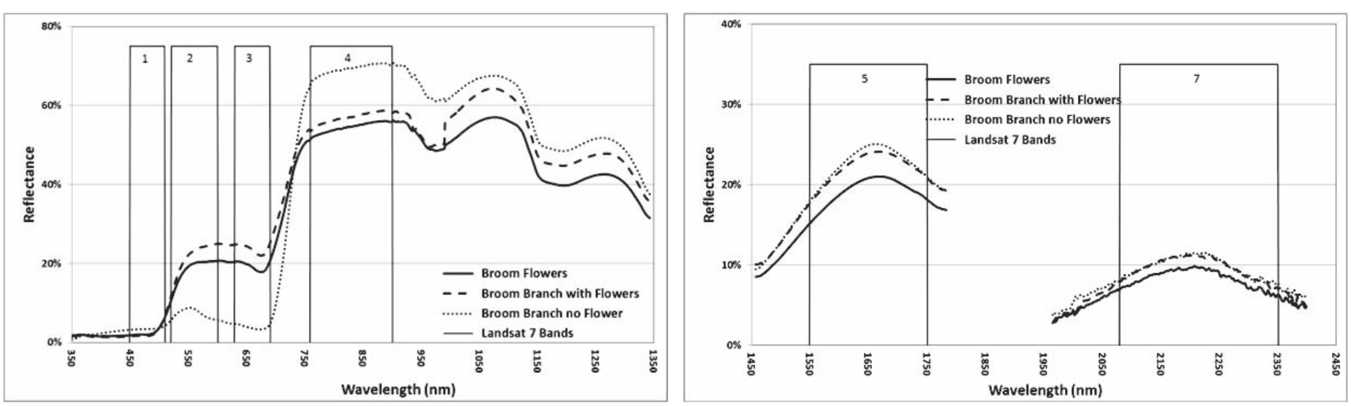


Figure 6. Mean value for pixels in all reference areas (training and test sites) of each class plotted for each Landsat band.

maximum likelihood classifier. The test set was used to calculate the accuracy of the classified data. Gorse is another invasive weed species of interest that has yellow flowers in the spring (Clements et al. 2001). Reference sites were created for the only two areas on Vancouver Island that are big enough to use on the Landsat imagery. The sample was an insufficient to use in classification, but the signatures and separability of the gorse class were examined.

Also available to check the general quality of the classification were existing survey data, including the British Columbia Ministry of Forests, Lands, and Natural Resource Operations (FLNRO) Invasive Alien Plant Program (IAPP) database, which consists primarily of point locations of reported Scotch broom observations (IAPP 2014). These are observations over many years. Additionally, a detailed year 2002 map was produced by the Capital Regional District of Vancouver Island using aerial sketch mapping at a scale of 1 : 10,000 for an 11 by 15-km area in the Sooke Watershed near Victoria (J Ussery, personal communication).

Field Spectrometer Measurements. Spectral reflectance measurements were acquired of Scotch broom plants and other vegetation cover with a FieldSpec® Pro FR spectroradiometer from Analytical Spectral Devices Inc. It is a portable spectroradiometer with a sampling interval of 1.4 nm from 350 to 1,000 nm and of 2 nm from 1,000 to 2,500 nm and a spectral resolution of 3 nm at 700 nm and 10 nm in the shortwave infrared, which covers the range of bands of the Landsat sensor (Figure 7). The spectroradiometer field of view was 25°. For measurement of Scotch broom and other plants, readings were taken from a step ladder approximately 1.5 m above the plants, giving a footprint size on the order of 65 cm. Spectral measurements of plant components such as flowers and branches with leaves were also taken. In this case, the plant components were stacked thickly on a dark background, and a reading was taken from typically 0.4 m away. All spectral measurements were calibrated to reflectance by comparing the readings to those of a barium sulfate reference reflectance panel. The reference panel was measured before and



a) b)

Figure 7. Spectral reflectance of Scotch broom plant components and Scotch thistle leaves and stems. Spectral bands of Landsat 5 and 7 are also shown. (a) 350 to 1,350 nm; (b) 1,450–2,400 nm.

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after each set of plant readings. Twenty-one spectra of each sample were recorded, and the average value was used. The spectroradiometer samples were obtained on June 20, 2001. This was shortly after peak coloration of the Scotch broom. Sky conditions were clear with a few scattered clouds.

The spectra for samples of Scotch broom plant components (Figure 7) were Scotch broom branches with leaves and flowers, branches with leaves and no flowers, and flowers only. Spectra of the Scotch broom plant at varying stages of flowering were acquired, as were readings from surrounding vegetation, such as swordfern [*Polystichum munitum* (Kaulf.) C. Presl], Scotch thistle (*Onopordum acanthium* L.), wild red raspberry (*Rubus idaeus* L.), and combinations of vegetation types. Samples of the Scotch broom plants were chosen from plants that were still in full flower and others with varying levels of flowering, including with no flowers.

Spectral Band and Feature Selection Procedures. It is often advantageous in a classification to use a selection of bands that highlight differences among the classes of interest. In this study, the important criterion was distinguishing dense and moderate levels of Scotch broom from other land types in the region that might get confused with Scotch broom. Targeting the flowering stage as a differentiating feature for Scotch broom perhaps can lead to specific band ratios or spectral indices that take advantage of the spectral differences in the green and red spectral bands caused by the flowering. Thus, an analysis of the spectral separability of Landsat bands and various band combinations and ratios (features) was conducted.

Statistical separability of the Scotch broom classes (dense, moderate, and low) among each other and with other land cover classes, as represented by the training and test areas, was the main feature used as selection criteria. The specific measure applied was the Jeffries-Matusita (JM) distance (Richards 1993), which ranges from 0, for no separability of two classes, to a maximum of 2.0, with values near 1 being considered moderate separability and greater than 1.7 good. For each selection of bands or band combinations (termed features), JM distance for dense, moderate, and low Scotch broom was calculated versus each of the other two Scotch broom classes and versus each of the 18 other land cover classes (Table 2). The average of the class pair JM distances for the dense, moderate, and low Scotch broom versus other classes was also determined. The effectiveness of a particular feature however is influenced by the user requirement in terms of mapping. For example, if one needs mainly to identify the dense or moderate patches, then low weight should be given to the ability of a feature to separate low-density Scotch broom. Moreover, some class pairs may be easy to separate with any band or feature, so the features with the best capability to distinguish the more difficult (least separable) classes should be favored. Sometimes the average class pair JM distance for a feature can be unduly influenced by one or two very high or low values and lead to selection of a nonoptimum feature. Known spectral reflectance differences, such as those noted from the ground-based spectroradiometer data, can reinforce the choice of feature or be used to identify specialized band combinations that might be effective. Therefore feature selection is not necessarily a straightforward process.

The separability of the individual Landsat bands, selected band combinations from one image date, various band ratios, and band combinations from bloom images and nonbloom images were examined. Band ratios and indices that might highlight the flowering stage were tested. These included band ratios involving the green, red, or both spectral bands with other bands, a variant of red and green band ratios called VARI (visible atmospherically resistant index), which is a vegetation index designed to reduce atmospheric effects (Gitelson et al. 2002), plus NDVI (normalized difference vegetation index), a common vegetation index (e.g., Table 3). The best combination of two through six Landsat bands was also determined by calculating the JM distance for every possible combination of bands.

Automated Classification and Accuracy Assessment Procedure. A standard pixel-based multispectral classification of the 22 cover type classes (Table 2) was conducted. It was a supervised classification with a maximum likelihood decision rule (Richards 1993). The training reference sites were used to establish the class statistics. The classifier of the PCI Geomatica image analysis software package was used (program MLC, PCI Geomatics, Richmond Hill, Ontario, Canada). All pixels were classified as one of the classes. Classifications were done using different feature sets on both the 2002 and 2003 bloom images on

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Table 3. Jeffries-Matusita (JM) distance between class pairs[a] of the Scotch broom classes (dense, medium, low) or the average JM distance between the Scotch broom classes and target non–Scotch broom classes. These are based on the June 2003 bloom Landsat imagery.[b]

	Average separability of class pairs (JM distance)					
Spectral feature[c]	Broom D vs. Broom M	Broom D vs. Broom L	Broom M vs. Broom L	Broom D vs. target nonbroom	Broom M vs. target nonbroom	Broom L vs. target nonbroom
1	0.010	0.120	0.062	0.525	0.546	0.648
2	0.553	0.977	0.270	1.026	0.553	0.461
3	0.531	1.095	0.345	1.162	0.926	0.784
4	0.086	0.032	0.015	0.429	0.349	0.358
5	0.197	0.102	0.206	1.061	0.838	0.916
7	0.115	0.058	0.168	1.033	0.930	0.955
1,2,3	0.613	1.238	0.468	1.756	1.363	1.133
2,3,4	0.651	1.191	0.418	1.639	1.239	1.001
3,4,5[d]	0.775	1.322	0.587	1.863	1.523	1.336
1,2,3,4	0.683	1.298	0.545	1.783	1.456	1.211
1,3,4,5[e]	0.787	1.369	0.662	1.884	1.572	1.401
1,2,3,4,5[f]	0.819	1.398	0.682	1.899	1.613	1.453
1,2,3,4,5,7	0.834	1.438	0.720	1.906	1.632	1.478
3/1	0.429	1.040	0.301	1.023	0.629	0.624
VARI	0.381	0.969	0.370	0.850	0.610	0.696
NDVI	0.855	1.413	0.913	1.921	1.824	1.744
(5 − 3)/(5 + 3)	0.499	0.899	0.118	1.159	0.597	0.553
5/4	0.030	0.018	0.076	0.980	0.866	1.015

[a] Broom D, Broom M, and Broom L are Scotch broom dense, moderate, and low classes, respectively; target nonbroom refers to target non–Scotch broom classes: shrub, regeneration, recent clearcut dense ground vegetation, recent clearcut moderate ground vegetation, recent clearcut sparse ground vegetation, recent clearcut bare, recent partial cut.

[b] Abbreviations: NDVI, normalized difference vegetation index; VARI, visible atmospherically resistant index.

[c] Landsat bands 1 (blue), 2 (green), 3 (red), 4 (near-infrared), 5 (shortwave infrared), 7 (shortwave infrared); band ratios 3/1, (5 − 3)/(5 + 3), and 5/4; indices VARI (2 − 3)/(2 + 3 − 1) and NDVI (4 − 3)/4 + 3).

[d] Best combination of three Landsat bands; band combinations 3, 4, 7 and 2, 3, 5 and 2, 3, 7 produced similar separabilities as the best combination (bands 3, 4, 5).

[e] Best combination of four Landsat bands; other four band combinations involving the red spectral band (3) and a shortwave infrared band (5 or 7) had similar separabilities.

[f] Best combination of five Landsat bands; all other five band combinations except the one without the red band had similarly high separabilities.

combined 2000 summer with 2002 bloom and 2000 summer with 2003 bloom image, and for combined 2003 summer with 2003 bloom imagery. It was thought that because Scotch broom distribution is affected by elevation, incorporating elevation might be useful. To test this, a simple classification was conducted using the elevation values of each pixel derived from a digital elevation model of the test area as an additional input feature. The same training areas were used for all dates and classification runs. Although all cover types were classified, the emphasis was on the results for the three Scotch broom concentration classes: low, medium, and dense. Differentiation of the medium and dense Scotch broom classes is useful, but more important is how effective the classifications are for detecting occurrences of Scotch broom. Thus the combined accuracy of the dense and medium Scotch broom classes was analyzed.

Accuracy was assessed by comparing the classification of the pixels within the test areas of each class to the true class of the test area. The focus of the classification was on identifying Scotch broom, and thus (1) how well the Scotch broom areas were classified as Scotch broom (i.e., how many pixels in the Scotch broom test areas did not get classified properly [percent omission]) and (2) whether test areas of other cover types were erroneously classified as Scotch broom (commissions or false alarms). In addition to the quantitative assessment, results were compared qualitatively to the oblique aerial photographs not used in creating the formal test areas and

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knowledge of cover types as determined from the oblique air photos, forest inventory maps, and knowledge of the local conditions. The classifications were also overlaid on British Columbia's Invasive Alien Plant Program map of reported Scotch broom locations. The "Capital Regional District of Vancouver Island" year 2002 sketch map of Scotch broom in the Sooke area was also checked against the classifications.

Pixel-based classifiers sometimes produce a considerable number of spurious isolated single pixels of a class or small patches of pixels of the same class. For a final map product, these are often reduced by applying a spatial filter to the classified pixels. Because Scotch broom can occur in small patches and a goal was to determine if moderate- and low-density Scotch broom can be mapped, any filtering process must be done carefully. PCI software routine Sieve (PCI Geomatics) was applied. It replaces single pixels and small groups of pixels of the same class with the dominant class of the surrounding pixels. First, the Scotch broom dense and Scotch broom moderate classes were temporarily combined into one Scotch broom class. Then, Sieve was applied to the classified pixels such that any areas of the merged Scotch broom class or Scotch broom low class less than three contiguous pixels (adjacent or corner connected) were merged into surrounding classes and thus eliminated. The remaining pixels of the combined Scotch broom class were then replaced with their original classification of Scotch broom dense or Scotch broom moderate. A classified and sieved Scotch broom map product was produced for selected classification runs.

Results and Discussion

Spectral Reflectance Data. The spectra of both the plant components and plants indicate that flowering Scotch broom have high reflectance, from 550 through 700 nm, giving the yellow coloration. As percent flowering decreased, reflectances progressed toward matching that of nonflowering Scotch broom. In the visible part of the spectrum, especially the green through red, the other ground vegetation like swordfern and Scotch thistle had higher or similar reflectance to the nonflowering Scotch broom. Spectra of other ground vegetation types will overlap with Scotch broom with low percent flowers; however, the flowering Scotch broom had flatter spectra in the 550 to 700 nm range. The red and green spectral bands of Landsat (bands 3 and 2) should show differences for Scotch broom with moderate or high levels of flowering, and band ratios involving band 2 and 3 may have useful information that takes advantage of the flatness of spectra of the flowering Scotch broom in these spectral regions. Indeed, the Landsat spectral signatures during the flowering period for sites of dense, moderate, and low Scotch broom concentrations (e.g., Figure 6) showed higher reflectances in the red and green spectral bands. Remember that these Landsat reference sites are Scotch broom mixed with other ground vegetation types and densities, with high-density Scotch broom having no or very little mixture with other surface types and low-density Scotch broom consisting mainly of other cover types.

In the near-infrared spectral region up to 1,350 nm, the plant component spectra showed Scotch broom branches without flowers as having higher reflectance than branches with flowers and the flowers themselves (Figure 7). However, for the spectra of the overall plant, reflectance decreased as the flowering level decreased. Alternatively, the Landsat spectral signatures (Figure 6) showed equivalent values for the reference sites of dense, moderate, and low Scotch broom density, indicating that, when Scotch broom is mixed with other ground vegetation types, any differences among sites of varying Scotch broom density caused by flowering are diminished. Shapes of the ground-based spectra of different Scotch broom levels showed little difference in the near-infrared. Plant spectra of mixed fern and thistle were high in the near-infrared, similar to full-bloom Scotch broom, and spectral shapes were similar, indicating an overlap of the spectra of flowering Scotch broom with other ground vegetation in the near-infrared.

In the shortwave infrared, reflectance of the flowers was lower than the branch with leaves and the branch with leaves and flowers, which were similar to each other (Figure 7). Scotch broom plants with different flowering levels differed, but these differences were smaller than for the green through near-infrared spectral regions. Spectral shapes were similar, and there was overlap with the spectra of other ground vegetation.

Spectral Band and Feature Selection. Class separabilities (JM distances) for the June 4, 2003, bloom image (Table 3) and the June 9, 2002, bloom data were generally similar and confirmed each other. The best combinations of bands and features were determined based on the average class pair separabilities of dense Scotch broom vs. moderate and low Scotch broom, plus dense Scotch broom vs. target non–Scotch broom classes that often have low separability with the Scotch broom classes (i.e., shrub, regeneration, and the four recent clearcut classes and recent partial cut). The best combinations of three through five spectral bands had higher separability than the individual bands (Table 3).

The best single band was the red band followed by green; the blue and near-infrared were poor with low JM distances (Table 3). Features derived from band ratios and band differences divided by band sums generally improved separability over the individual bands. Features utilizing the green and red vs. blue bands were effective, with the simple red/blue band ratio being the best. It was better than the green-blue ratio or ratio (red − blue)/(red + blue), which were also good. The VARI index involving the difference between the red and green band (see Table 3) and a simple (red − green)/(red + green) index were not very effective. Features involving ratios and differences between the shortwave infrared and near-infrared bands were also not effective (e.g., band 5/band 4; Table 3). Moderate to good separabilities (JM distances) were given by shortwave infrared vs. red band features, mostly benefiting from the spectral difference in the red band. An index (shortwave infrared [band 5] − red)/(shortwave infrared + red) was the best of the features tested involving the shortwave bands, but a similar index using shortwave band 7 and simple shortwave vs. red band ratios were almost equally good. The NDVI index was the best of all features tested (Table 3). It utilized the increase in reflectance in the red spectral region for flowering and similar or lower near-infrared reflectance vs. the other cover types. Utilizing the green band in the same way (near-infrared − green)/(near-infrared + green) was not nearly as effective.

If one only has an image during bloom, the best four-band combination was almost equally as good as all six bands (e.g., Table 3). The shortwave infrared bands of Landsat individually were of only moderate value, with an average JM distance of Scotch broom dense with target non–Scotch broom classes on the order of 1.0 (Table 3). However, in combination with the other bands, they were important. For example, the best two-band combination was the red and shortwave infrared band 5 combination with an average JM distance of Scotch broom dense with target non–Scotch broom classes of 1.81. Simple three- or four-band visible and near-infrared band combinations, as in most high-resolution satellite systems, produced high separabilities but were less discriminating than those with shortwave infrared. Select band ratios were effective and better than the single bands. Those involving the near-infrared and red bands, like NDVI, were very good and should be included in classifications. NDVI had a JM distance for Scotch broom dense vs. target nonbroom classes of 1.92 (Table 3).

The summer no-bloom July 2000 image alone using all six Landsat bands showed low to very low separability of the different densities of Scotch broom from each other, along with low separabilities for Scotch broom vs. shrub and recent partial cuts, and moderate to low Scotch broom vs. the clearcut classes, brown grass, and some bare rock (Table 4). The July 2000 summer image in combination with an image during the flowering period, however, produced better separability than the single bloom image (Table 4). This was the case for July 2000 combined with both bloom 2002 as well as with bloom 2003 data, which produced similar results. This combination utilized two factors: (1) in the bloom image the Scotch broom differs spectrally from the other cover types, whereas during the summer they are more similar and (2) reflectance from the spring bloom image to summer changes for the Scotch broom but is not much different for the other cover types. A summer no-flowering image complements a flowering image and should be used when such imagery is available.

Classification and Accuracy. Classification results showed qualitatively over all the different classifications tested (e.g., Figure 5) that the pattern of classified bloom followed known areas of Scotch broom. Some pixels were falsely classified as Scotch broom in areas of shrub and some recent clearcuts. The moderate Scotch broom class also had a pattern of erroneous pixels along old logging roads that were closed in with hardwoods or ground vegetation. Spurious areas of low Scotch broom, especially

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Table 4. Separabilities (JM[a] distances) for Scotch broom classes vs. other cover types for nonbloom summer 2000 image, bloom 2002 and 2003 imagery, plus combined summer 2000 with bloom 2002 and summer 2000 with bloom 2003 images. All six bands were used from each date of imagery.

	July 2000			June 2002			June 2003			Bloom–nonbloom (July 2000–June 2002)			Bloom–nonbloom (July 2000–June 2003)		
Class	Scotch broom dense	Scotch broom mod.	Scotch broom low	Scotch broom dense	Scotch broom mod.	Scotch broom low	Scotch broom dense	Scotch broom mod.	Scotch broom low	Scotch broom dense	Scotch broom mod.	Scotch broom low	Scotch broom dense	Scotch broom mod.	Scotch broom low
Scotch broom dense	—	0.474	0.709	—	0.742	1.115	—	0.834	1.438	—	1.130	1.548	—	1.031	1.668
Scotch broom moderate density	0.474	—	0.564	0.742	—	0.494	0.834	—	0.720	1.130	—	0.969	1.031	—	1.017
Scotch broom low density	0.709	0.564	—	1.155	0.494	—	1.438	0.720	—	1.548	0.969	—	1.668	1.017	—
Shrub	0.935	0.721	0.703	1.766	1.317	1.191	1.796	1.254	1.055	1.874	1.531	1.417	1.928	1.585	1.423
Regeneration	1.753	1.807	1.444	1.912	1.766	1.507	1.942	1.842	1.098	1.985	1.952	1.775	1.997	1.972	1.553
Recent clearcut dense vegetation	1.615	1.633	1.277	1.781	1.352	1.221	1.843	1.307	1.407	1.964	1.868	1.709	1.990	1.883	1.796
Recent clearcut moderate vegetation	1.128	1.098	0.566	1.735	1.218	0.944	1.870	1.430	1.635	1.894	1.647	1.303	1.963	1.730	1.766
Recent clearcut sparse vegetation	1.346	1.308	0.977	1.826	1.417	1.098	1.959	1.777	1.898	1.936	1.795	1.611	1.994	1.949	1.977
Recent clearcut bare	1.228	1.501	1.366	1.936	1.814	1.663	2.000	1.997	1.999	1.978	1.958	1.933	2.000	2.000	2.000
Recent partial cut	0.746	0.738	0.480	1.787	1.207	0.992	1.837	1.350	1.433	1.878	1.594	1.449	1.936	1.692	1.679
Brown grass	1.471	1.363	1.394	1.887	1.617	1.371	1.956	1.740	1.881	1.961	1.837	1.834	1.978	1.876	1.962
Bare rock	1.353	1.190	1.331	1.924	1.635	1.605	1.986	1.878	1.952	1.981	1.870	1.834	1.996	1.953	1.985
Bare soil	1.918	1.990	1.963	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
Crop	1.989	1.994	1.942	1.871	1.955	1.905	1.965	1.765	1.787	1.996	2.000	1.997	1.995	1.949	1.960
Green grass	1.682	1.673	1.335	1.875	1.757	1.629	1.899	1.459	1.571	1.973	1.964	1.903	1.983	1.798	1.828
Urban	1.498	1.674	1.604	1.925	1.825	1.699	1.918	1.801	1.819	1.968	1.944	1.874	1.972	1.917	1.926
Softwood	1.930	1.971	1.859	1.999	1.995	1.949	1.992	1.985	1.825	2.000	1.999	1.983	1.999	1.999	1.947
Hardwood	1.966	1.971	1.939	1.981	1.985	1.981	1.969	1.908	1.659	1.999	1.998	1.999	1.996	1.985	1.874
Mixedwood	1.560	1.587	1.512	1.946	1.867	1.740	1.930	1.820	1.252	1.978	1.941	1.863	1.984	1.948	1.619
Averages of JM distances between Scotch broom class and other classes															
Most difficult non–Scotch broom classes[b]	1.179	1.111	0.884	1.791	1.342	1.144	1.860	1.416	1.482	1.914	1.695	1.542	1.959	1.753	1.725
Target non–Scotch broom classes[c]	1.254	1.218	0.908	1.801	1.379	1.159	1.874	1.493	1.421	1.922	1.731	1.544	1.968	1.802	1.699
All non–Scotch broom classes	1.507	1.514	1.356	1.884	1.670	1.531	1.929	1.707	1.642	1.960	1.869	1.780	1.982	1.890	1.831
All classes including other Scotch broom classes	1.406	1.403	1.276	1.780	1.533	1.452	1.841	1.604	1.579	1.891	1.778	1.722	1.912	1.793	1.777

[a] Abbreviations: JM, Jeffries-Matusita; mod., moderate.

[b] Most difficult non–Scotch broom classes are shrub, recent clearcut dense ground vegetation, recent clearcut moderate ground vegetation, recent partial cut, and brown grass.

[c] Target non–Scotch broom classes (without recent clearcut bare) are shrub, regeneration, recent clearcut dense ground vegetation, recent clearcut moderate ground vegetation, recent clearcut sparse ground vegetation, recent partial cut.

Table 5. Classification results for different feature sets. The *training reference sites vs. test* used training reference sites for generating the statistics (signatures) used for the classification and used the test reference sites to test accuracy.

	Producer accuracy (training reference sites vs. test)				
Classification[a]	Scotch broom dense	Scotch broom moderate	Scotch broom low	Combined Scotch broom dense and moderate	Scotch broom Dense classified as dense or moderate
BNB all six bands, NDVI, and DEM	66.9	47.4	28.8	81.9	91.1
BNB all six bands and NDVI	66.2	45.4	33.2	81.1	91.0
BNB all six bands	62.4	50.6	38.5	81.8	89.8
BNB bands 3,4,5,7	56.7	47.4	36.4	77.6	87.9
BNB bands 1,2,3,4	66.2	44.7	29.8	79.3	89.8
BNB bands 1,2,3,4 and NDVI	70.1	42.0	27.1	79.4	91.8
June 2003 all six bands and NDVI	69.4	39.8	27.4	76.4	93.0
June 2003 all six bands	63.1	45.9	28.8	79.4	94.9
June 2002 all six bands	59.2	38.0	24.8	71.1	82.1
June 2003 bands 1,2,3,4	63.1	40.7	18.2	77.3	94.3
June 2003 bands 1,2,3,4 and NDVI	68.8	34.8	13.0	72.9	90.5

[a] Abbreviations: BNB, classifications using Scotch broom and non–Scotch broom imagery from June 2003 and July 2003; NDVI, normalized difference vegetation index; DEM, digital elevation model.

within urban areas, likely arose from pixels that were partly vegetated and partly developed or contain shrubs. The spatial filtering (Sieve) process applied to the classification was unable to eliminate erroneous areas of Scotch broom completely. The larger patches classified as Scotch broom, regardless of class, however, represented actual areas of Scotch broom, and patches of Scotch broom larger than 0.5 ha seemed to be captured. The different classifications corresponded in the pattern and location of larger Scotch broom units. Importantly, this was true for classifications mapping 2002 Scotch broom distribution vs. those mapping 2003 Scotch broom, indicating that the process was repeatable over different years and images.

Quantitative accuracies of different classifications vary (Table 5). For example, when compared with the test areas, accuracies of the three Scotch broom classes were 59.2, 38.0, and 24.8 for dense-, moderate-, and low-density Scotch broom, respectively, for the classifications using all six spectral bands of the June 2002 image and were 63.1, 45.9, and 28.8, respectively, for the June 2003 imagery. Confusion matrices were produced for each classification (e.g., Table 6). Only the portion of the confusion matrix relevant to the Scotch broom classes are presented (Table 6). Producer accuracy gives the percentage of pixels in the test areas of each of the three Scotch broom classes classified as each of the 21 land cover classes. User accuracy gives the percentage of pixels in the test areas of each of the 21 classes that are classified as one of the three Scotch broom classes.

Accuracy of the low-density class ranged from 25 to 38% (e.g., Table 5), with considerable commission error labeling non–Scotch broom areas as Scotch broom. Use of the Scotch broom low class would cause an overestimate of Scotch broom area. For reliable mapping, it is likely best not to include a low class. However, if detection is required and false alarms (commissions) are preferable over missing occurrences (omissions), then a low-density Scotch broom class might still be useful. Much of the commission error in the classifications can easily be interpreted as spurious through context and manual interpretation of the imagery (e.g., the low-density Scotch broom class appearing in urban developed sites). Separation of moderate- and high-density Scotch broom produced confusion of approximately 25% (i.e., typically 20 to 30% of dense or moderate Scotch broom being classified as the other). However, for many applications, it is just the presence of moderate- or high-density Scotch broom that is important. Accuracy of these classes combined was 71% for the 2002 bloom image classification with all six bands and 79% for June 2003 (Table 5). The Scotch broom dense class was very reliable in terms of having Scotch broom; typically over 90% of the Scotch broom dense test pixels were classified as either Scotch broom dense or moderate (Table 5).

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Table 6. Confusion matrices for Scotch broom dense, moderate, and low vs. each other and other cover classes. Producer accuracy is the percentage of all pixels in the test areas of a Scotch broom class classified as each of the 21 cover classes (e.g., of the 157 pixels in the Scotch broom dense test sites, 66.2% were classified as Scotch broom dense or 33.8% were omissions not classified correctly as Scotch broom dense). User accuracy is the percentage of all pixels in the test areas of a class that were classified as Scotch broom (e.g., of the 316 test pixels of the shrub class, 0.3% were committed or falsely classified as Scotch broom dense).[a]

Cover Type	Scotch broom dense	Scotch broom moderate	Scotch broom low	Shrub	Regeneration	RCC dense vegetation	RCC moderate vegetation	RCC sparse vegetation	RCC bare
June 2003 all bands and NDVI									
Producer accuracy									
Scotch broom dense	66.2	23.6	4.5	0	0.6	0	0	0	0
Scotch broom moderate	24.0	44.7	14.3	2.5	0	0.2	0	0.2	0
Scotch broom low	3.2	17.2	29.8	2.7	16.4	6.8	2.3	0.2	0
User accuracy									
Scotch broom dense	66.2	24.0	3.2	0.3	0	0	0	0.2	1.0
Scotch broom moderate	23.6	44.7	17.2	5.7	0.4	2.4	7.2	3.4	0.2
Scotch broom low	4.5	14.3	29.8	11.4	6.9	0.6	17.6	0.4	0
No. of pixels	157	405	621	316	2,764	336	250	536	629
BNB bands 1,2,3,4 and NDVI									
Producer accuracy									
Scotch broom dense	69.4	23.6	4.5	0	0.6	0	0	0.6	0
Scotch broom moderate	20.0	39.8	13.6	3.0	0	2.2	5.2	4.4	0
Scotch broom low	5.2	13.2	27.4	2.4	29.8	6.4	0.3	1.0	0
User accuracy									
Scotch broom dense	69.4	20.0	5.2	0.3	0	0	0	0.2	0
Scotch broom moderate	23.6	39.8	13.2	7.6	0	5.4	9.2	0.7	0
Scotch broom low	4.5	13.6	27.4	11.7	6.5	3.3	8.4	0	0
No. of pixels[b]	157	405	621	316	2,764	336	250	536	629

[a] Abbreviations: RCC, recent clearcut; NDVI, normalized difference vegetation index; BNB, classifications using Scotch broom and non–Scotch broom imagery from June 2003 and July 2003.

[b] Number of pixels in test areas of a class.

The most common confusion in terms of false alarm (i.e., areas not Scotch broom classified as one of the Scotch broom classes) were areas of shrub, brown grass, and recent clearcuts with moderate-density or dense ground vegetation being classified as moderate Scotch broom (e.g., Table 6, User accuracy, Scotch broom moderate row). The Scotch broom dense class had very few false alarms, whereas commission error for the Scotch broom low class was considerable with several cover types. It was also noted qualitatively that hemlock regeneration in the study region often exhibited a visually yellow tinge, as observed on the ground and on the Landsat normal color images, especially on poorer sites. These would occasionally have Scotch broom erroneously classified within. Omission error (i.e., areas that are truly Scotch broom misclassified as one of the other cover classes) was generally low, with very few Scotch broom dense areas being classification as another cover type, and only small amounts of moderate Scotch broom areas being classified as shrub or recent clearcut with moderate and dense ground vegetation and sometimes recent partial cuts (e.g., Table 6, Producer accuracy, Scotch broom moderate row). Similar to commissions, in terms of omission classification, accuracy of Scotch broom low was lower with considerable areas of Scotch broom low classified as other cover types. On the order of 45 to 50% of test pixels of low Scotch broom were classified as one of the non–Scotch broom classes.

The above accuracies are for classifications not filtered to eliminate very small patches of classified Scotch broom. A filtering process was applied, as one might do to produce a final map product for some applications (i.e., sieved to eliminate one- and two-pixel patches classified as Scotch broom). This did improve the classification in terms of commissions. It eliminated many small erroneously classified patches, especially in areas of shrub and recent clearcuts with ground vegetation. For example, comparing classification accuracies for the 2003

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Table 6. Extended.

Recent partial cut	Brown grass	Bare rock	Bare soil	Crop	Green grass	Urban	Softwood	Hardwood	Mixedwood	Water	Snow	No. of pixels[b]
0	0	0	0	0	0	5.1	0	0	0	0	0	157
5.4	0.7	0.5	0	1.5	2.7	2.5	0.5	0	0.2	0	0	405
2.6	0.2	0.5	0	0.2	3.2	1.9	0.2	5.0	7.7	0	0	621
0	1.2	0	0	0	0.8	0	0	0	0	0	0	
1.9	6.7	0	0	0.3	2.9	0.1	0	0.3	1.2	0	0	
2.7	0.6	0.9	0	1.3	1.1	0	0.6	9.3	9.3	0	0	
377	163	114	95	2,364	631	8,941	7,655	291	507	126,663	949	
0	0	1.3	0	0	0	0	0	0	0	0	0	157
2.5	0	0.5	0	1.5	6.2	1.2	0	0	0	0	0	405
2.4	0	0.8	0	0.8	3.5	1.4	0	1.1	4.2	0	0	621
0	0	0	0	0	0	0	0	0	0	0	0	
1.1	3.7	0	0	0.5	1.3	0.1	0	0	0.6	0	0	
1.6	0.6	0	0	0.1	0.6	0	0	0	3.2	0	0	
377	163	114	95	2,364	631	8,941	7,655	291	507	126,663	949	

bloom classification using all six bands with and without sieving indicated that the sieving process did not cause more omissions and reduced commissions. Commissions were approximately halved for the moderate Scotch broom class and reduced from very small to near nil for Scotch broom dense. For Scotch broom low, false alarms were still high but were improved by 10 to 15%.

Application Considerations. Overall, results indicate that methods based on Landsat imagery and utilizing the yellow coloration of the flowering period may have some value in mapping and monitoring Scotch broom. Low-density Scotch broom intermixed with other vegetation will not be reliably classified. Small patches of Scotch broom will often be missed, and there will be spurious small patches falsely classified as Scotch broom. The classification can be tailored to favor the detection of small areas at the expense of creating false alarms or vice versa; nevertheless, the method using Landsat imagery will have little value in early detection of small patches < 0.5 ha. Depending on resources available and importance, high-resolution satellite or even airborne imagery could be utilized. Medium-resolution satellite data, as in this study, could perhaps predict where outbreaks are occurring, or might occur, to limit the search area and prioritize the area over which high-resolution imagery is acquired.

Accuracies for detecting Scotch broom patches > 0.5 ha (dense or moderate class) as either a Scotch broom dense or moderate class are expected to be near 80%. Areas classified as the Scotch broom dense class had high concentrations of Scotch broom (typically 90% of test pixels of Scotch broom dense were classified as either Scotch broom dense or moderate). It was shown that results can be consistent and repeatable over time; the 2 yr of imagery tested (2002 and 2003) gave comparable results. Using all spectral bands of Landsat and the NDVI index from an image during bloom and a second image in the summer after bloom is recommended, but Table 5 gives the results that can be expected with a single image during bloom and with satellite systems with only visible and near-infrared spectral bands. It is possible that the number of false alarms could be reduced with manual

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interventions, such as use of forest inventory or available high-resolution imagery from Bing Maps or Google Earth to determine whether areas where Scotch broom has been classified are suitable to supporting Scotch broom. Confusion of Scotch broom with regenerating areas of hemlock and spurious pixels classified as Scotch broom in the forest away from potential mechanisms of Scotch broom spread can be eliminated. Recent clearcuts or partial cuts are easily identifiable on the Landsat imagery, and the known tendency toward false alarm classifications of Scotch broom in these cover types can be used to note these as potentially erroneous pixels of Scotch broom. With field checking, especially through aerial observation, the level of accuracy could be increased and an accurate and precise map made.

The spectral reflectance measurements, Landsat spectral band separability analyses, and classification trials indicate that the use of yellow flowering is essential for distinguishing Scotch broom. The drawback of using spring flowering for detection is the limited time window of the yellow coloration. An approximate 30-d period occurs during which coloration is likely to be sufficient. For the Landsat satellite, this gives two to three acquisitions. Results show that the shortwave spectral band of Landsat is useful, but sensors with visible and near-infrared bands are adequate. Thus, other medium-resolution satellites such as SPOT, Resourcesat, China–Brazil Earth Resources Satellite, Disaster Monitoring Constellation, and future systems like Sentinel provide suitable alternatives. The capability to use a variety of systems increases the probability of acquiring suitable imagery in the flowering window and the viability of the method.

Possible Improvements. A number of improvements are possible over the methods developed and tested in this study. Multiple classifications of Scotch broom from different years using summer and bloom imagery would produce several versions of Scotch broom distribution that can be used to confirm sites, especially small Scotch broom patches. For example, if a small isolated patch only occurs on one of three classifications, it could be assigned as suspect or not Scotch broom. A more robust classification would result. With a time series of classifications over 5 to 10 yr, one would obtain high confidence and the reliability for monitoring spread or changes in Scotch broom distribution would increase. Multiple years of mapping would also help resolve some of the variability of detected Scotch broom from different spatial distributions of the timing of flowering and flower drop. Moreover, a time trend in spectral feature values over 5 to 10 yr could perhaps be used to confirm Scotch broom sites and identify new incursions. Methods are now available for assembling time series of Landsat imagery and processing it in such a way as to select the best available pixel (e.g., White et al. 2014). The best available pixel for a given year in the case of Scotch broom detection could be defined as the pixel from all spring Landsat imagery not affected by cloud, cloud shadow, or haze, that is closest in date to peak flowering for that year. This date could be different for different regions of a study area based on latitude, elevation, or local factors. Alternatively, one could develop a system for selecting pixels from the imagery that have the highest degree of yellowness based on pixels in areas of known Scotch broom. In this example, if two or three images were available during the flowering period, for example, the pixels used might be a mix from all three images optimizing the capability for detecting Scotch broom. The pixels representing the summer nonbloom conditions could be defined as the image closest to a midsummer date and also unencumbered by cloud or haze. Note that it is desirable but is not necessary that the summer image used in a bloom–no bloom classification be from the same year as the bloom image.

One of the limitations of the method developed using Landsat data is detection of small patches of Scotch broom and low concentrations of Scotch broom. At 30-m resolution and with the disparate distribution of Scotch broom, this is inevitable. High-resolution satellites usually have multispectral modes with three or four visible and near-infrared bands and resolutions of 1 to 5 m. Table 5 gives the classification results for Landsat imagery using only visible and near-infrared band sets and whether a red band and NDVI index are included. The spatial detail available on high-resolution RapidEye imagery is much higher that with Landsat (e.g., Figure 8). Thus, using high-resolution imagery should improve spatial detail and the capability to detect low concentrations of Scotch broom. However high-resolution sensors have narrow swath widths, and data are expensive for coverage of large areas.

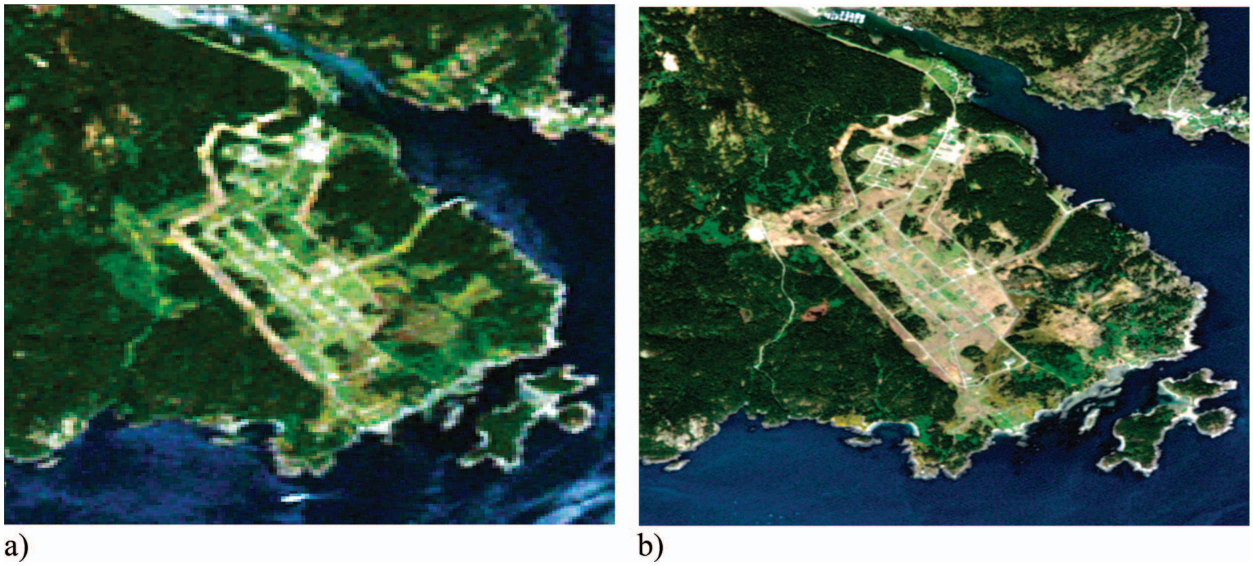

Figure 8. (a) Landsat 30-m resolution image June 4, 2003, 2 wk past full bloom. (b) RapidEye 6.5-m resolution image April 23, 2011, 2 wk before full bloom. Both are normal color renditions with the red, green, and blue spectral bands displayed as red, green, and blue.

Scotch broom distribution is affected by its biological limitations and mechanisms of spread. These could perhaps be used to modify the remote sensing classification results. For example, the Scotch broom class could be restricted to areas below a given elevation or within certain temperature limits. In this study, the classification trial using elevation as a simple input feature did improve classification accuracy. Proximity to roads or other corridors like pipelines and power lines could be used as a parameter governing the probability of Scotch broom being present. Presence of existing Scotch broom could also be a criterion.

Relevance to Scotch Broom Management Activities. With or without improvements, the approach can provide estimates of Scotch broom location useful to varying degrees dependent on the application. It appears that it can provide effective information on the spatial extent and distribution of Scotch broom for those monitoring invasive plants, and Scotch broom, in particular, can give data potentially useful for remediation programs and fire control and can provide information for policy and land management decisions. Indeed, the map product of this study has contributed to the knowledge base of land managers on Vancouver Island by providing improved information on the spatial extent and density of Scotch broom. The approach is also likely good for monitoring, say on a 5-yr basis, as a record of its spread and severity over time. This in turn can provide insight into the causes of spread and likely site types and actual locations susceptible to spread. The basic approach is likely adaptable to other locations in the world where Scotch broom occurs and potentially other invasive species characterized by distinct, albeit ephemeral, color differences.

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