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Monitoring soil disturbance on salvaged areas within the mountain pine beetle infestation using digital imagery

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Abstract. There is a concern that the accelerated timber harvest in the mountain pine beetle epidemic area of British Columbia (BC) could compromise long-term forest productivity if soils are unduly disturbed. Consequently, the Ministry of Forests, Lands and Natural Resources Operations (MFLNRO) developed a protocol using ground- and image-based methods to assess the status of the forest soil resource in part of the BC Forest and Range Evaluation Program (FREP). Although this protocol uses high-resolution aerial imagery, the MFLNRO is also collecting beetle imagery at a smaller scale for detecting and monitoring. For this evaluation, we use a combination of ground- and imagery-based assessments as developed for FREP within the BC Interior Plateau. We determined that low-resolution data are useful and are sufficient for detecting and measuring the extent of roads and landings. Areas occupied by landslides, erosion, drainage diversion, inordinate disturbance, or roadside work areas can be captured on remote-sensed images with spatial resolution greater than 2.5 m. However, based on this review and previous work, aerial photographs in 10-cm pixel size are best suited to reveal less evident harvesting-related soil disturbance. © The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI. [DOI: [10.1117/1.JRS.7.073541](https://doi.org/10.1117/1.JRS.7.073541)]

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1 Introduction

The cumulative area of British Columbia (BC) that was affected to some degree by the mountain pine beetle (MPB) is estimated at 18.1 millions ha, and the Ministry of Forests, Lands and Natural Resources Operations (MFLNRO) predicts that 57% of the provincial lodgepole pine (*Pinus contorta*) inventory could be killed by 2021—these trees make-up over half the BC Interior’s annual harvest.¹ To lessen the impacts of the forest health crisis, the BC MPB Action Plan included a provision to recover the greatest value from dead timber before it burns or decays, while conserving the long-term forest values identified in land-use plans.²

The resulting accelerated timber harvest in the MPB epidemic area could compromise long-term forest productivity as wet soil conditions have expanded.³ With less interception and evapotranspiration, dead and dying lodgepole pine stands experience changes in water balance resulting in more soil moisture, a quicker hydrological response to precipitation events, and a greater frequency of increased water.⁴ Where soils “water up,” there is a higher risk of compaction and rutting during salvage operations.⁵

To evaluate if current forest practices conserve and protect soils in BC at the local scale, a monitoring process was put in place that measures soil-based indicators developed to assess the effectiveness of forest and range legislation in achieving stewardship objectives.^{6,7} Indicators provide a protocol to assess changes in soil conditions in line with international standards and criteria for sustainable forest management set out by the Montreal Process.^{8–11} Indicators

are assessed through soil disturbance observable on the ground as proxy for longer-term effects, and therefore, provide a qualitative assessment of soil productivity and hydrologic function within the last two years after harvesting at the cutblock level.⁶ Measuring indicators are done mostly using high-resolution air photography in 10-cm pixel size to provide a rapid evaluation of soil attributes. A ground-based survey can complement the air photo review when site conditions are not favorable, i.e., certain disturbances are not visible on brush-rich grounds from scarifying the mineral soil to remove surface organic materials.

High-resolution air photography provides crisp-quality image for the assessment of soil disturbance at the local scale, but must be acquired specifically for a project. Their utility has been shown for measuring small-scale disturbance in forestry.^{12,13} However, they are not readily available as satellite imagery. Additionally,, high-resolution air photography is costly considering quality satellite imagery are becoming increasingly available (i.e., IKONOS), and some are being provided for free or at reasonable cost over the Internet.¹⁴⁻¹⁶ Within the context of the information needed, the immediate goal of the current project was to investigate whether there are sources of data other than highly pixelated aerial photography (e.g., <10 cm resolution) that can be used to identify and map soil disturbance indicators following salvage harvesting using the imagery analysis method developed for Forest and Range Evaluation Program (FREP).

In this research, we examined available remote-sensed images of different spatial resolution with respect to (1) level of recognition and (2) accuracy assessment of indicators of soil conservation in association with harvesting activities within MPB areas.

2 Methodology

2.1 Data

The FREP Soil Resource Stewardship Monitoring method is organized into five key indicators, which provide an objective and representative evaluation of productive and hydrologic function of soils at cutblock level under BC's *Forest and Range Practices Act*.⁷ This is primarily an image-based survey method that focuses on indicators that rely on features that can be easily distinguished in remote-sensed images, i.e., are visible from overhead. Table 1 highlights those indicators for describing the status of soils on recently logged cutblock.

Indicators were assessed across a range of digital image formats ranging from satellite imagery to low-altitude aerial photography with pixel size between 10 cm and 30 m (also referred to by spatial resolution of 30 × 30 m² frame, Table 2). The lower the spatial resolution frame (or the higher the resolution of the data), the smaller is the visible feature that can be captured. For example, coarse woody debris lying on the ground is visible in a 10-cm pixel size, whereas within a larger pixel of 30 × 30 m² a large feature can be detected. A total of 95 images were analyzed across 23 random cutblocks. Each cutblock came with at least two image data types to a maximum of five.

Images were in TIFF format, which is an uncompressed format commonly used for image-manipulation, and geo-referenced to allow for direct measurement of distances, areas, and

Table 1 Cutblock-level indicators of soil conservation included in the image-based method of Soil Resource Stewardship Monitoring.

Indicators of soil conservation
<ul style="list-style-type: none"> • Lost productivity due to access construction • In-block area affected or potentially affected by landslides, drainage diversion, or erosion • Soil disturbance hazards, dispersed disturbance, inordinate disturbance, and roadside work areas • Green tree retention • Dead wood

Table 2 Images accessed for monitoring indicators of soil conservation across selected forest districts.

Image format (pixel size)	Mackenzie	Prince George	Vanderhoof	Rocky Mountain
Landsat 5 TM (30 m) ^a	14	16	8	4
SPOT 5 (15 m) ^b	0	0	4	0
SPOT 5 (5 m)	0	8	4	0
SPOT 5 (2.5 m)	0	8	0	0
BC orthophoto (1 m) ^c	2	0	4	0
Aerial photo (0.5 m) ^d	0	0	4	0
Aerial photo (0.1 m) ^e	7	8	0	4
Total number of images	23	40	24	8
Total number of blocks	7	8	4	4

^aLandsat 5 Thematic Mapper (TM) satellite color image (2004 and 2005), National Oceanic and Atmospheric Administration, USA.

^bSPOT 5 (Satellite Pour l'Observation de la Terre) black and white image, spatial resolution of 15 × 15 m², 5 × 5 m², and 2.5 × 2.5 m², SPOT Image Corporation, USA.

^cBC orthophoto is a geometrically corrected aerial photograph provided by the BC government in color or black and white.

^dLow elevation true color aerial photography taken with vertical camera system provided by TDB, <http://www.tdb.bc.ca>.

^eLow elevation true color aerial photography taken with vertical camera system by J. Heath, Terrasaurus Aerial Photography, <http://www.terrasaurus.ca/>.



Fig. 1 Map of northern, central, and eastern British Columbia (BC), Canada. Locations of study sites are shown with a symbol "K."

position. Images are available to the general public, and can be ordered using the Base Map Online Store except for those of high resolution, i.e., less than 1-m pixel size.¹⁷ High-resolution aerial photographs acquired locally for this study used a fixed-wing aircraft, and will be accessible to the general public once the data is audited for quality assurance.

Image analysis aimed to identify and map indicators of soil disturbance was performed by an end-user with limited knowledge in soils, but was assisted by an experienced photo-interpreter. Some remote-sensed data were field verified for quality assurance. Accuracy of measurement was examined only for access structures (key indicator 1, Table 1) from various image formats based on comparisons with the highest-resolution image available for each block (equal or very close to the true value on the ground). Means and standard deviations of access structure estimates were computed in Microsoft Excel (2007) using the AVERAGE and the STDEV functions, respectively.

Images were loaded into *OziExplorer* GPS Mapping software, and processed to evaluate cutblock-level indicators (Table 1).¹⁸ The software was selected for its low cost and user friendliness for maps containing geo-referenced information and real-tracking ability with a GPS receiver for work in the field. Using *OziExplorer*, we can determine the size of features and areas, and prepare a map showing the location of soil disturbance types (e.g., landings).

2.2 Study Area

The study area is mostly located in the central part of the interior plateau, which lies in the rain shadow of the BC Coast Mountains. Between 800 and 1400 m above sea level, the landform is rolled with few high peaks, and parent materials are mostly consolidated and of glacial origin. Precipitation can be as little as 250 mm annually in the valleys, but can reach 750 mm or more on western slopes. Soils are frozen in the winter, but in the summer soils “water-up” due to increased delivery of precipitation to the ground as the MPB affected trees die.¹⁹ Additional salvaged areas were added to the sample population just to the east of the Interior Plateau in the southern Rocky Mountains, where digital imagery was also available and site disturbance field data existed to confirm the photo interpretation. During the summer months, in each cutblock, clearcut harvests were implemented, and trees were felled mechanically and yarded to the roadside areas for processing. Ground survey results presented in this study are based on the BC Soil Conservation Survey Guidebook.²⁰ The study focused in forest districts, where the MPB outbreak was important within the Vanderhoof, Mackenzie, Rocky Mountain, Prince George, 100 Mile House, Central Cariboo, and Chilcotin Forest Districts (Fig. 1).

Table 3 Identifiable features from different remote-sensed image format in relation to soil indicators.

Image format	Access structure	Areas of landslides, drainage diversion, or significant erosion	Inordinate disturbance and roadside work areas	Green tree retention	Dead wood
Landsat 5 TM (30 m)	Visible ^a	Not visible	Not visible	Visible ^a	Not visible
SPOT 5 (15 m)	Visible	Not visible	Not visible	Visible	Not visible
SPOT 5 (5 m)	Visible	Not visible	Not visible	Visible	Not visible
SPOT 5 (2.5 m)	Visible	Visible	Visible	Visible	Not visible
BC orthophoto (1 m)	Visible	Visible	Visible	Visible	Not visible
Aerial photo (0.5 m)	Visible	Visible	Visible	Visible	Not visible
Aerial photo (0.1 m)	Visible	Visible	Visible	Visible	Visible

^aApplies to roads only. Landings become clear at 5-m pixel size unless significantly greater than 0.2 ha in size.

^bApplies to green tree retention in patches. Single-tree retention is best observed at 50 cm and at a smaller pixel size.

3 Results

3.1 Identifiable Features

In central BC, we were able to find randomly 23 sites that had been salvage harvested and where digital imagery was acquired within 1 year of harvest. The amount of information available in each remote-sensed image is a function of its lowest object detail. The spatial resolution of some images limits the number of indicators that can be evaluated (Table 3). Access structures, particularly roads, and green tree retention in patches are evident on all remote-sensed images, but easier to discern on aerial photographs (Fig. 2). On Landsat 5 Thematic Mapper (TM) color images (30 m), roads are generally represented by dark pink pixels, whereas tree retention stands out in green. Exposed soils in landings and roads yield a brighter spot than the surrounding areas on black and white SPOT 5 (Satellite Pour l'Observation de la Terre) images. Surface wetness from drainage diversion displays as a darker color due to poor reflection response and, unfortunately, often blends in with natural ingress and brush making interpretation difficult.

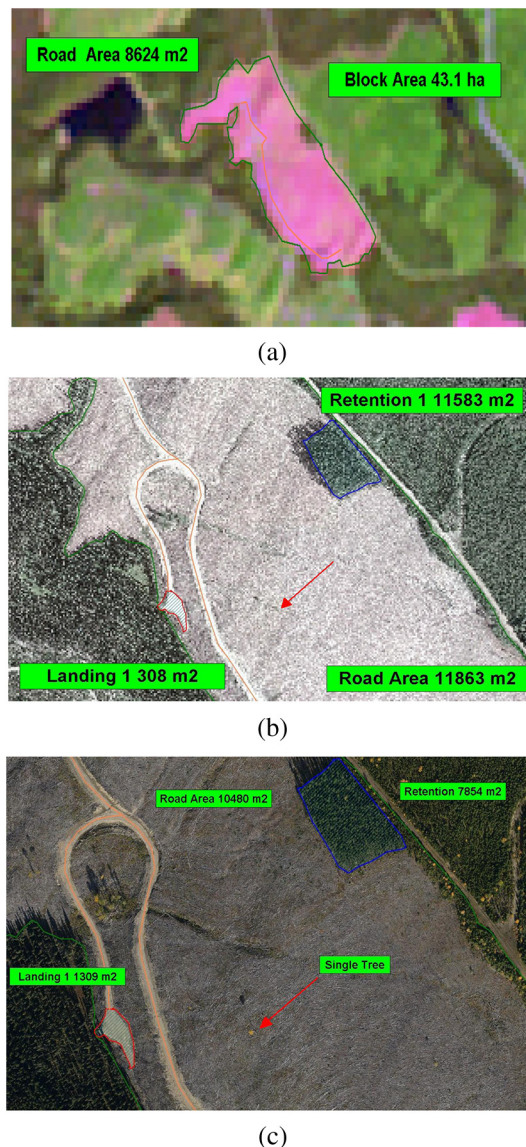


Fig. 2 Examples of access structure and green tree retention on Mackenzie cutblock #239: (a) Landsat 5 Thematic Mapper (TM) (30 m), (b) BC orthophoto (1 m), and (c) aerial photo (0.1 m).

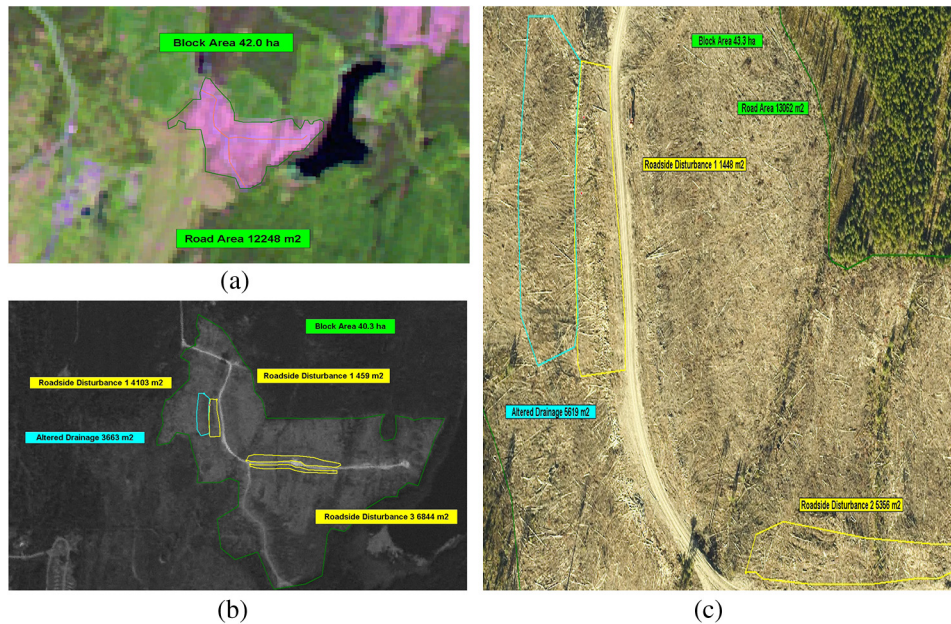


Fig. 3 Lynx Lake cutblock in Prince George Forest District showing smaller areas of soil disturbance such as altered drainage and roadside work areas: (a) Landsat 5 TM (30 m), (b) SPOT 5 (2.5 m), and (c) aerial photo (0.1 m).

Small areas (<0.2 ha) where soil has been disturbed, such as landings and inordinate disturbance areas, often appeared fuzzy and blended in with other ground features on low-resolution images with a pixel size greater than 2.5 m (Table 3). In comparison, wheel ruts and skid trails are clearly visible on higher-quality images less than 1-m pixel (Fig. 3). They were mostly found near or within roadside work areas and often contributed to impeded natural drainage patterns. High-resolution data greater than 1-m pixel size allow discernment of single-tree retention. All other indicators of soil conservation, except for dead wood, escape notice on satellite images until pixel size equaled 2.5 m. Higher quality images facilitate detection of other disturbances such as areas of altered drainage and roadside work areas (Fig. 3). A spatial resolution of 10×10 cm² is best suited for assessing the amount of dead wood (Fig. 4).

3.2 Accuracy of Measurements

The accuracy of remote-sensed images for measuring roads and landings varies with the image format. Here, accuracy of measurements refer to how close the measured value is to the true or accepted value, not to be confused with positional accuracy which is an assessment of the closeness of the object's location in relation to its true position on the Earth's surface. Estimation of the amount of roads varied with standard deviation between 6% and 40% (Table 4). On a block-by-block basis, the largest variation was found in Landsat TM images as a result of the large field of view (30×30 m²) and poor differentiation of color tones (e.g., logging road width is less than 30 m). It has the lowest data resolution of remote-sensed data used in our study. However, on an average, satellite images performed nearly as well as any other remote-sensed images for measuring roads (percent difference from actual values as low as 6%, Table 4), although their detection is not as easy as with high-resolution images (Fig. 2).

The area occupied by landings identified from the different image formats was between 3% and 26% lower than the area identified from the reference high-resolution photo (Table 4). However, there is a large source of variation (standard deviation up to 44%, Table 4) associated with the estimates for the same reasons as roads. Overall, moderate-resolution data between 1 and 5-m pixel size are sufficient for estimating areas occupied by landings (Table 4) when no higher-resolution images are available.

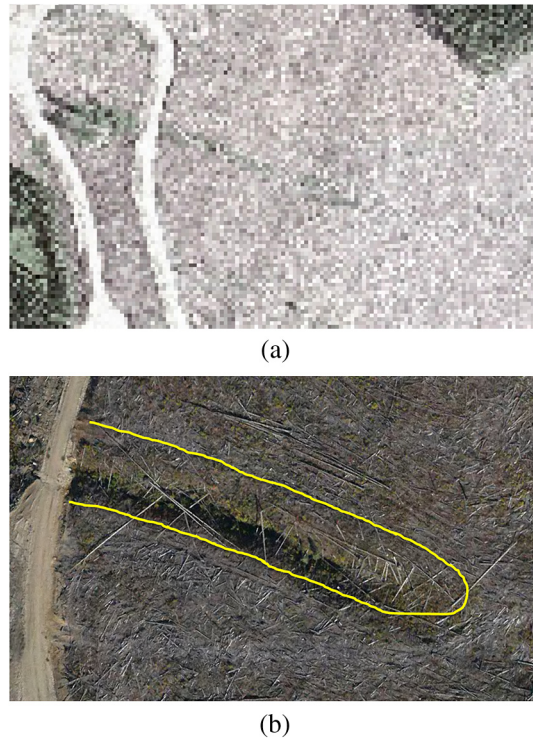


Fig. 4 Coarse woody debris across a gully on Mackenzie block #239: (a) BC orthophoto (1 m) and (b) aerial photo (0.1 m).

Table 4 Variability in estimating loss of productivity due to access structure using five remote-sensed image formats when compared with a reference photo (STD = standard deviation).

Image format	Roads		Landings	
	Average difference (%)	STD (%)	Average difference (%)	STD (%)
Landsat 5 TM (30m)	-3 ^a	40	-26	44
SPOT 5 (15 m)	-1	6	No landings	No landings
SPOT 5 (5 m)	6 ^b	25	-3	44
SPOT 5 (2.5 m)	2	26	-7	39
BC orthophoto (1 m)	-5	15	-10	28

^aA negative value means that estimates underestimate reference photo value.

^bA positive value means that estimates overestimate reference photo value.

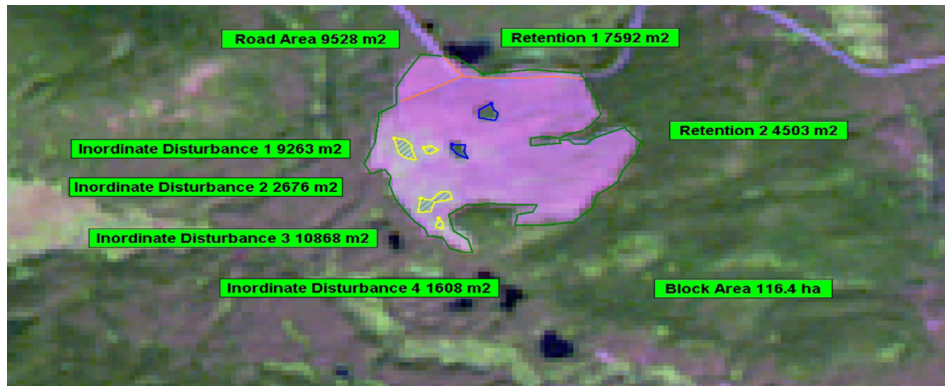
4 Discussion

Aerial photos (<50 cm pixel size or approximately 1:16,000) show the more obvious types of soil disturbance quite clearly, whereas the more subtle kinds of disturbances, i.e., when forest floor layers are still present, make it difficult to interpret compaction. Knowing the textural composition of the soil is important to assess compaction. However, soil texture cannot be extracted from an image (i.e., without a remote spectral signature). Rutting and other machine traffic were then used as proxy indicators of compaction.

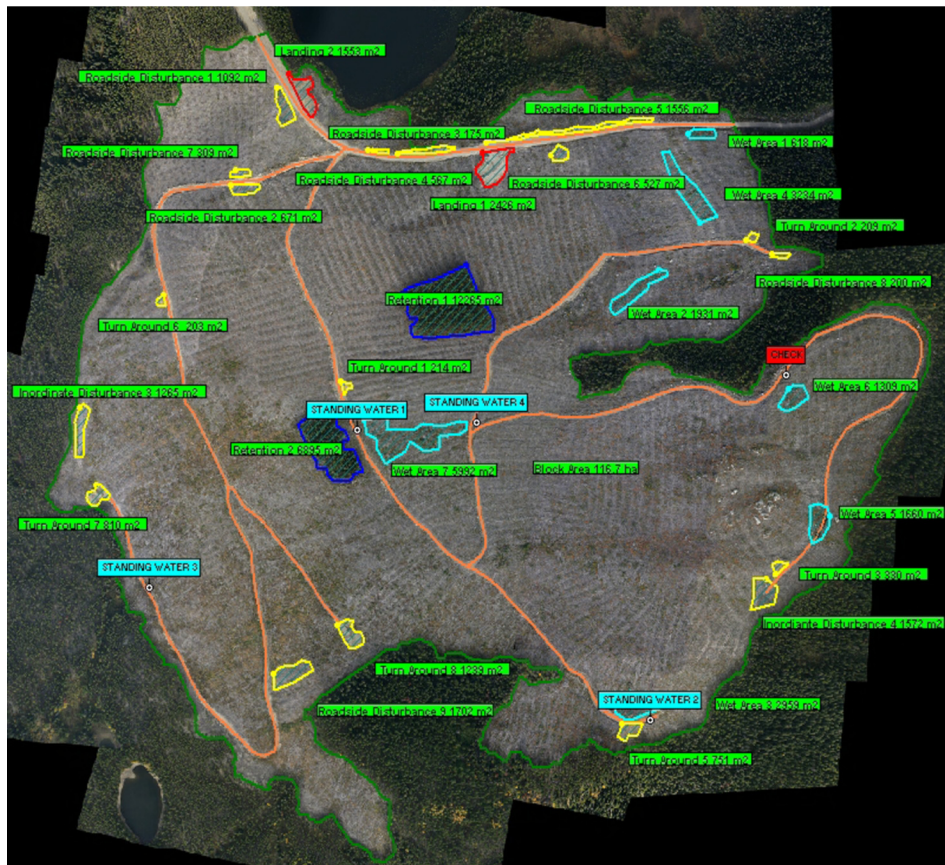
Ground surveys for soil disturbance were conducted on 5 of the 23 sampled cutblocks to validate our results. The method using aerial photos succeeded to identify blocks that had significant amounts of soil disturbance (e.g., ruts and gouges) ranging from 8.1% to 49.1% of the net area to be reforested. Except for Landsat TM, satellite imagery, although less pixelated, was adequate to pick up roads and patches of tree retention. We were confident that both satellite

imagery of 15 m resolution or less and high-resolution aerial photography were able to show actually what was there on the ground.

To get the most from remote-sensed images used for detecting soil disturbance, one needs to understand that spatial resolution limits the amount of information (i.e., the level of details that can be detected from a selected image format) (Fig. 5). Satellite imagery trades off quality against ground coverage in one swath (e.g., Landsat TM 185-km width versus small area coverage low elevation aerial photography), although pixel size as well as positional accuracy—not examined here—are rapidly increasing with advanced sensor technology. As a result, smaller size features, such as landings, were sometimes identified incorrectly as a result of fuzzy boundaries in the satellite image, something not observed on aerial photographs. These “hits and misses” can impact



(a)



(b)

Fig. 5 (a) Landsat 5 TM image (30 m) provides limited information. Even permanent access structures are very difficult to identify. (b) The same block mapped at 10-cm pixel resolution from an aerial photo.

the estimates, but not significantly in the case of access structure considering that landings receive a smaller weight compared with roads in the computation of access structure due to their small size.

Overall, satellite images provided acceptable results for tracking productivity losses on access structures (Fig. 3). Although the amount of green tree retention patches were not assessed between image formats, our work suggests its accuracy would be similar to that of access structures. This review indicates that aerial photographs are more suited to map indicators other than loss of productivity due to access structures (e.g., areas affected by landslides, drainage diversion, or erosion), because there is less difficulty in distinguishing soil features from slash, brush, and natural regeneration or microrelief.²¹ High-resolution satellite imagery like SPOT 5 with pixel size ranging from 2.5 to 5 m could be useful, with an understanding that some information can be missed. However, newer satellite sensors such as GeoEye-1 (0.41 m) and IKONOS (0.82 m) may detect finer detailed features, and therefore, potentially be useful for estimating indicators that require a higher level of discrimination.²²

Good visibility of soil features in satellite images also depends on other factors. Local variation in terrain slope will influence how objects are reflected and captured by the sensors. In smaller blocks, various elements such as tree edge, landings, roads, or topography are present in one pixel and as a result, influence signal return producing a complex response making interpretation difficult (Fig. 6). With spatial resolution data less than or equal to $5 \times 5 \text{ m}^2$, roads running along cutblock boundaries are sometime difficult to map because they are obscured by the tree crowns. The appearance of the ground on satellite images also depends on weather conditions as satellites

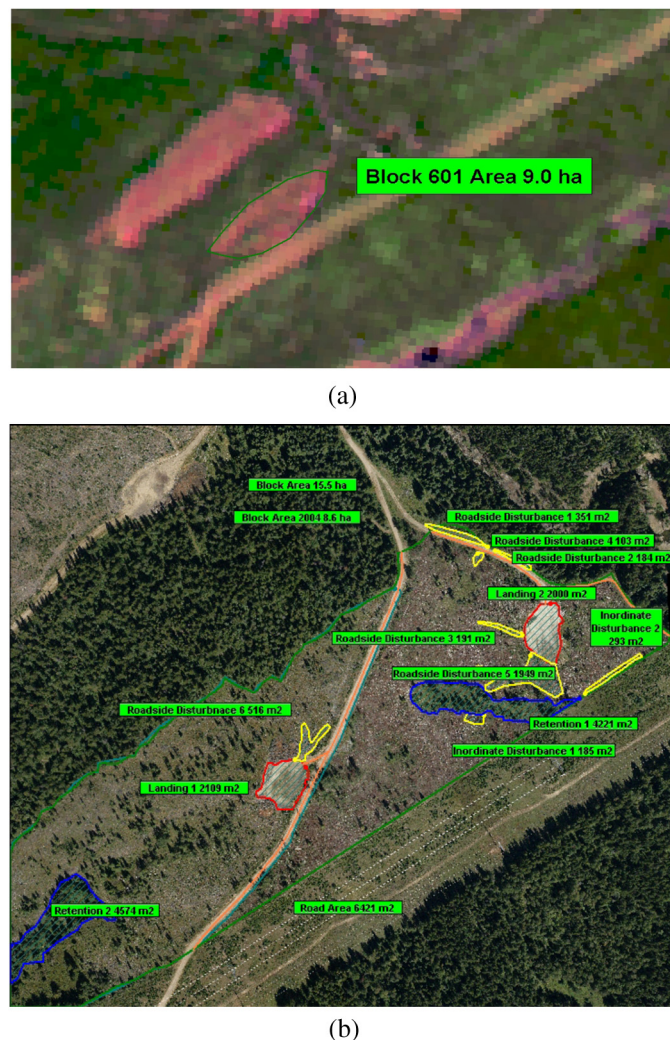


Fig. 6 (a) A Landsat 5 TM (30 m) image of Cranbrook block showing how block size affects the amount of identifiable features, in comparison with (b) high-resolution aerial photo (0.1 m).

follow predetermined orbital passes and work on a fixed schedule. Figure 7 illustrates that detection can be difficult on a cloudy or hazy day. In contrast, aerial photograph can be taken whenever the sky is clear but ground coverage is limited, and the cost of acquiring them is generally higher than that for satellite photos. Whether or not one image format is more appropriate than another one should be decided by the user's needs because information that can be derived from each image format is limited by its spatial resolution.

5 Management Implications

The extreme level of soil disturbance found in at least one block suggests that there may be a very good reason to be concerned about the level of soil disturbance associated with salvage harvest operations. This level of soil disturbance would never be considered acceptable for normal timber harvesting, and it is important to determine what harvest operations were used on this cut-block and if it is indicative of increased soil disturbance caused by the changes in hydrologic function of the site. We were able to identify and measure soil disturbance using both satellite imagery and low-level aerial photography. Therefore, digital imagery can be used to assess the overall state of soil management in relation to salvage harvesting.

Information needs should guide the choice of an appropriate data source for monitoring soil conservation following salvage operations within MPB-affected areas. Moderate resolution satellite imagery between 15 and 30 m (e.g., Landsat 5 TM) would be likely sufficient for detecting and

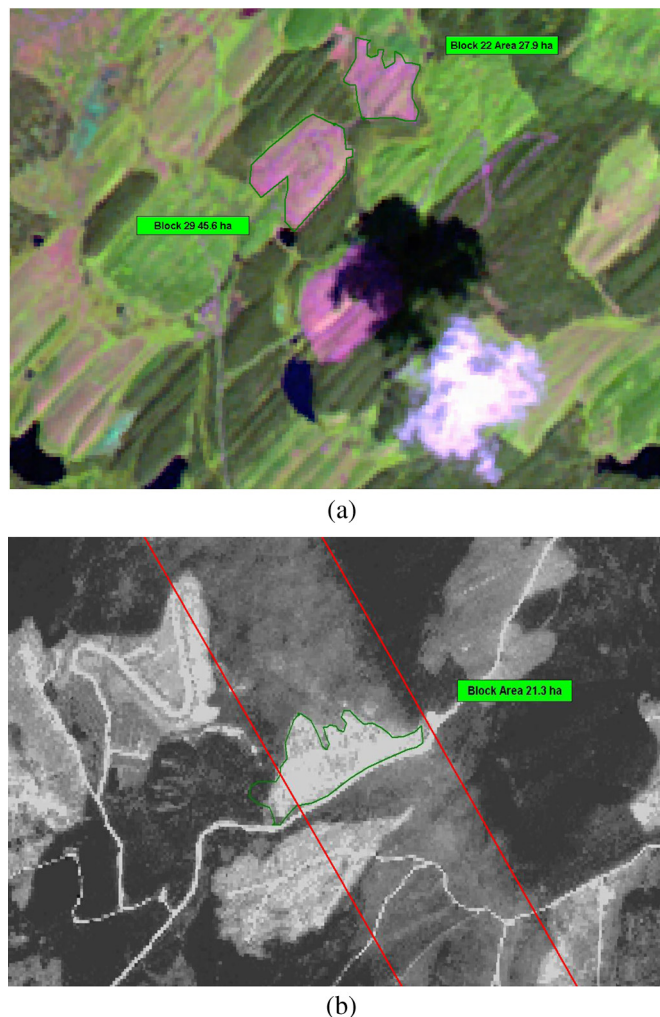


Fig. 7 Weather conditions affected feature identification: (a) A cloud on a Landsat 5 TM image and its associated shadow, and (b) a cloud patch (outlined in red) on a SPOT 5 (2.5 m).

measuring the extent of roads and landings. Finer images provide higher accuracy measurements if necessary. Areas occupied by landslides, erosion, drainage diversion, inordinate disturbance, or roadside work areas can be captured on remote-sensed images with spatial resolution greater than 2.5 m, such as SPOT 5, and 1-m pixel size image, such as BC government orthophotos.

Based on this research and previous work, aerial photographs are best suited to describe and accurately assess the less-evident harvesting-related soil disturbance. Higher-resolution data deliver the best information for end-users, but costs and availability will also need to be considered before making a final decision.

The information presented in this study was obtained from manual digital images interpretation, which is a process that has its limitations.²² As digital imagery evolves to provide finer details, techniques such as classification (either pixel- or object-based) or digital elevation model (e.g., ConMap) can complement manual interpretation to achieve accuracy gain in soil mapping.²³ Our method will contribute information to the Montreal Process-Member Countries in evaluating the protective and productive functions of forests in relation to soil and water resources (Criterion 2—maintenance of productive capacity of forest ecosystems and Criterion 4—conservation and maintenance of soil and water resources).¹¹

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References

1. Ministry of Forests, Lands, and Natural Resource Operations, "Facts about BC's Mountain Pine Beetle," 2012, http://www.for.gov.bc.ca/hfp/mountain_pine_beetle/Updated-Beetle-Facts_April2013.pdf (23 May 2013).
2. Ministry of Forests, Lands, and Natural Resource Operations, "Mountain Pine Beetle action plan," 2006, http://www.for.gov.bc.ca/hfp/mountain_pine_beetle/Recovering_Value_from_Dead_Timber.htm (23 May 2013).
3. J. Rex, S. Dubé, and V. Foord, "Mountain Pine Beetles, salvage logging, and hydrologic change: predicting wet ground areas," *Water* **5**(2), 443–461 (2013), <http://dx.doi.org/10.3390/w5020443>.
4. R. D. Winkler et al., "Mountain Pine Beetle, forest practices, and watershed management," BC Ministry of Forests, and Range, Research Branch, Victoria, B.C. Extension Note 88, 2008, <http://www.for.gov.bc.ca/hfd/pubs/Docs/En/En88.htm> (23 May 2013).
5. W. M. Aust et al., "Soil physical and hydrological changes associated with logging a wet pine flat with wide-tired skidders," *Southern J. Appl. Forestry* **17**(1), 22–25 (1993).
6. M. Curran et al., *Protocol for soil resource stewardship monitoring: cutblock level*, Forest and Range Evaluation Program, BC Ministry of Forests and Range and BC Ministry of Environment, Victoria, BC, <http://www.for.gov.bc.ca/ftp/hfp/external!/publish/frep/indicators/Indicators-Soils-Protocol-2009-May26-2009.pdf> (2009).
7. C. Bulmer et al., "Monitoring the effects of forest practices on soil productivity and hydrologic function," *BC J. Ecosyst. Manag.* **9**(2), 48–59 (2008).
8. J. A. Burger and D. L. Kelting, "Using soil quality indicators to assess forest stand management," *Forest Ecol. Manag.* **122**(1–2), 155–166 (1999), [http://dx.doi.org/10.1016/S0378-1127\(99\)00039-0](http://dx.doi.org/10.1016/S0378-1127(99)00039-0).
9. D. Page-Dumroese et al., "Soil quality standards and guidelines for forest sustainability in northwestern North America," *Forest Ecol. Manag.* **138**(1–3), 445–462 (2000), [http://dx.doi.org/10.1016/S0378-1127\(00\)00430-8](http://dx.doi.org/10.1016/S0378-1127(00)00430-8).
10. S. H. Schoenholtz, H. Van Miegroet, and J. A. Burger, "A review of chemical and physical properties as indicators of forest soil quality: challenges and opportunities," *Forest Ecol. Manag.* **138**(1–3), 335–356 (2000), [http://dx.doi.org/10.1016/S0378-1127\(00\)00423-0](http://dx.doi.org/10.1016/S0378-1127(00)00423-0).

11. The Montreal Process, "Criteria, and indicators for the conservation, and sustainable management of temperate, and boreal forests," 2nd ed., December 1999, http://www.montrealprocess.org/documents/publications/general/1999/1999santiago_e.pdf (23 May 2013).
12. P. Teti, "Novel aerial photography as an aid to sampling secondary structure in pine stands," Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Victoria, BC, Mountain Pine Beetle Working Paper 2009-16, 2009, <http://cfs.nrcan.gc.ca/pubwarehouse/pdfs/30122.pdf> (23 May 2013).
13. M. A. Wulder, J. C. White, and N. C. Coops, "Information-need-driven applications of remotely sensed data for mapping mountain pine beetle infestation at landscape and tree levels," Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Victoria, British Columbia, Information Report BC-X-410 (2007).
14. C. E. Woodcock et al., "Free access to Landsat imagery," *Science* **320**(5859), 1011 (2008), <http://dx.doi.org/10.1126/science.320.5879.1011a>.
15. GeoBC Gateway, <http://geobc.gov.bc.ca> (23 May 2013).
16. TerraServer®, <http://www.terraserver.com/home.asp> (23 May 2013).
17. British Columbia Base Map Online Store, <http://www.basemaps.gov.bc.ca> (23 May 2013).
18. OziExplorer software, D&L Software Pty Ltd., Australia, <http://www.ozieplorer.com> (23 May 2013).
19. S. Dubé, A. P. Plamondon, and R. L. Rothwell, "Watering up after clear-cutting on forested wetlands of the St. Lawrence lowland," *Water Resour. Res.* **31**(7), 1741–1750 (1995), <http://dx.doi.org/10.1029/95WR00427>.
20. BC Ministry of Forests, "Soil conservation surveys guidebook," 2nd ed., Forest Practices Branch, BC Ministry of Forests, Victoria, BC, 2001, <http://www.for.gov.bc.ca/tasb/legsregs/fpc/fpcguide/soilsurv/soil-toc.htm> (23 May 2013).
21. J. L. Morgan, S. E. Gergel, and N. C. Coops, "Aerial photography: a rapidly evolving tool for ecological management," *BioScience* **60**(1), 47–59 (2010), <http://dx.doi.org/10.1525/bio.2010.60.1.9>.
22. N. C. Coops and C. W. Bater, "Remote sensing opportunities for estimating indicators of forest sustainability," FREP, BC Ministry of Forests, and Range, Victoria, BC, Report #21, 2009, http://www.for.gov.bc.ca/ftp/hfp/external!/publish/frep/reports/FREP_Report_21.pdf (23 May 2013).
23. T. Behrens et al., "The ConMap approach for terrain-based soil mapping," *Eur. J. Soil Sci.* **61**(1), 133–143 (2010), <http://dx.doi.org/10.1111/ejs.2010.61.issue-1>.



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