Delineating Areas of Past Environmental Degradation near Smelters using Rock Coatings: A Case Study at Rouyn-Noranda, Quebec

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Emissions of SO\textsubscript{2} from smelters can promote formation of acid rain, which can dissolve siliceous minerals on exposed rock surfaces and promote the formation of silica gel layers within which detrital and smelter-derived particulates can become trapped. These processes of dissolution and entrapment can result in the formation of rock coatings that contain elevated levels of heavy metals. Between 1927 and 1976, the Horne smelter processed sulfide ore derived from the Rouyn-Noranda region and became one of the largest emitters of particulates and sulfur dioxide in North America, promoting the formation of coatings on nearby rock surfaces. The reflectance spectra of these coatings are relatively flat, with typical reflectance values ranging between ~5% at visible wavelengths and ~16% in the shortwave infrared. Absorption troughs in coating spectra are consistent with the presence of materials including opaline silica, olivine, pyroxene, hydrous phyllosilicates, and sulfates. Classification of Landsat 8 Operational Land Imager data indicates that rock coatings near Rouyn-Noranda comprise a total surface area of ~1.5 km\textsuperscript{2}, nearly all of which is located within ~6 km of the Horne smelter. Remote sensing techniques can be used to delineate the geographic extents of coatings near smelters, highlighting areas previously subjected to severe environmental degradation.

The use of remote sensing techniques in the detection and mapping of rock coatings near smelters can help to delineate the geographic extents of areas subjected to past environmental degradation, and has the potential to be applied toward the monitoring of ongoing degradation at sites where emissions continue to promote the development of coatings\textsuperscript{11,12}. Related techniques may also prove useful in the monitoring of environmental recovery where smelter emissions have been reduced. In prior work, the supervised classification of Landsat Enhanced Thematic Mapper Plus (ETM+) and Hyperion satellite images was successfully used to determine the spatial distribution of rock coatings near three smelting sites in the Sudbury region of Ontario, Canada, highlighting areas previously exposed to relatively high levels of acid rain and smelter-derived particulates\textsuperscript{11,12}.

This study extended the scope of earlier work at Sudbury, Ontario, to the Rouyn-Noranda region of Quebec (Fig. 1), in order to further evaluate remote sensing techniques in the detection, mapping, and characterization of past environmental degradation near the Horne smelter in the Rouyn-Noranda region of Quebec.

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of rock coatings near smelters. Between 1927 and 1976, the Horne smelter processed sulfide ore derived from the Rouyn-Noranda region and ultimately became one of the largest emitters of particulates and sulfur dioxide in North America\textsuperscript{13,14}, negatively affecting local vegetation vigor and extent\textsuperscript{15,16} and contaminating surface materials with heavy metals\textsuperscript{17–19}. Over time, coatings formed on exposed rock surfaces proximal to the Horne smelter\textsuperscript{20}.

In this study, the reflectance spectra of rock coatings from the Rouyn-Noranda region were measured and described, and were compared with those previously collected for the Sudbury region. Also, a reflectance database derived from Landsat 8 Operational Land Imager (OLI) data for this region was classified in order to determine the spatial distribution of rock coatings produced by the Horne smelter, and to further evaluate the utility of remote sensing techniques in the study of environmental degradation caused by smelters.

The Rouyn-Noranda Study Area

The Rouyn-Noranda study area is 35 km by 20 km in dimension and is approximately centered on the Horne smelter (Fig. 2), which is located on the western shores of Lac Osisko and within the city of Rouyn-Noranda, Quebec. Bedrock of the northern and central parts of the study area is dominated by Archean igneous materials of the Blake River Group, a southern unit of the Superior Province’s Abitibi greenstone belt\textsuperscript{21,22}. Further to the south are predominantly sedimentary units of the Timiskaming and Cadillac groups (both also part of the Abitibi greenstone belt), the Cobalt Group (a Paleoproterozoic unit of the Huronian Supergroup), and the Pontiac Group (a northern unit of the Pontiac Subprovince)\textsuperscript{23,24} (Fig. 2). The Abitibi greenstone belt has mostly been subjected to low-grade metamorphism and predominantly displays greenschist to subgreenschist facies\textsuperscript{25,26}. Cobalt Group materials within Quebec have similarly been subjected to low-grade metamorphism\textsuperscript{27}, but the Pontiac Subprovince is of medium metamorphic grade near its northern boundary with the Abitibi greenstone belt\textsuperscript{28}.

The 2.7 Ga Blake River Group mainly consists of volcanic units of basaltic to rhyolitic composition\textsuperscript{26,29}. All associated lava flows are interpreted to have been emplaced in a submarine environment, based in part on the widespread occurrence of pillow lavas and pillow breccias (including hyaloclastites) and the presence of turbidite and argillite interbeds\textsuperscript{26,30}. Volcanic units of the Blake River Group were intruded by several generations of plutons, dikes, and sills\textsuperscript{26}, with the most prominent intrusions including the Flavrian and Powell tonalites and the Lac Dufault granodiorite\textsuperscript{29,31} (Fig. 2).

The Blake River Group hosts more than thirty volcanogenic massive sulfide (VMS) deposits\textsuperscript{26,31}. In the Rouyn-Noranda region, these VMS orebodies are associated with rhyolite flows and felsic fragmental rocks of the Noranda volcanic complex\textsuperscript{29,31–33}, a 35-km-diameter volcanic center composed of alternating mafic and felsic units that are crosscut by dikes of gabbroic and dioritic composition\textsuperscript{34,35}. The related Horne deposit is one of the world’s largest VMS orebodies, having produced 260 tonnes of gold and 1.13 megatonnes of copper between 1927 and 1976\textsuperscript{35}. Ore minerals associated with the Horne and nearby VMS deposits include pyrite, pyrrhotite, chalcopyrite, galena, sphalerite, and magnetite, as well as native gold and silver\textsuperscript{32,36}.

The study area is located in the boreal ecoclimatic region of Canada\textsuperscript{37}. Topographic relief here is less than 150 m, and bedrock exposure is discontinuous. Glacial lakes Ojibway and Agassiz-Ojibway extended across much of western Quebec in the Early Holocene, and glaciofluvial, glaciolacustrine, and glacial till deposits are variously distributed across parts of the study area\textsuperscript{38,39}. The study area falls within the balsam fir and white birch domain of...
the boreal vegetative zone, with common tree types including white spruce, black spruce, balsam fir, aspen, birch, and jack pine. Lichen cover can be extensive on local bedrock.

The Horne Smelter. The Horne smelter (Figs 2 and 3A) processed local sulfide ore between 1927 and 1976, and during this time frame became one of the largest North American emitters of particulates and sulfur dioxide. Metals released into the atmosphere during and following this period have most notably included lead, zinc, nickel, arsenic, copper, and cadmium. Annual emission of particulate matter here peaked in 1965 at more than 1.5 million metric tonnes. Pollution controls were implemented at the Horne smelter beginning in the 1970s, resulting in reductions in total emissions. The Horne smelter ceased the processing of local sulfide ores in 1976, and over the following decades became a processor of electronic scrap containing copper and precious metals.
As with emissions of particulate matter, annual emissions of sulfur dioxide peaked in 1965 at about 710,000 metric tonnes, and have steadily declined since that time. In areas proximal to the Horne smelter, such emissions have previously stunted the growth of trees and affected the abundances of some varieties of vegetation (e.g., reducing or eliminating the presence of Sphagnum fuscum peat moss). Smelter emissions may have also increased the acidity of some lakes in the region. Soils, peat hummocks, aquatic organisms, and seasonal snow in the Rouyn-Noranda region have contained elevated levels of heavy metals both during and following the period of peak annual emissions, with metal concentrations generally decreasing with increasing distance from smelter stacks.

Rock Coatings Near the Horne Smelter. Acid rain generated near the Horne smelter prior to the mid-1970s interacted with exposed rock surfaces to form thin silica gel layers, causing the entrapment of detrital and smelter particulates within gel layers and additionally promoting the formation of metal sulfate layers. Over time, these processes promoted development of prominent rock coatings with colors that range between black and reddish-brown. Rock coatings in the Rouyn-Noranda region are most commonly 5 to 50 micrometers thick, and are predominantly composed of a silica-rich matrix that likely consists of opal and cristobalite and within which a diverse range of particulates is embedded. Particulates are variously composed of minerals such as detrital quartz, hematite, muscovite, clinochlore, amphiboles, and feldspars, and the presence of high-temperature spinels such as magnetite and silicates such as olivine and pyroxene is expected. Metal sulfate layers are typically present along coating surfaces, within coatings, or at interfaces between coatings and underlying substrates.
Zinc\textsuperscript{20}. Boundaries between silica-rich layers and underlying rock are generally sharp, which suggests that the coatings formed through an evaporation-dissolution-reprecipitation process\textsuperscript{8,10,20,55}.

Coating thicknesses in the Rouyn-Noranda region are generally a function of both rock composition and distance from the Horne smelter. In particular, coatings tend to be thickest on mafic substrates, and are mostly limited to smelter distances of less than \textasciitilde6 km\textsuperscript{20}. Since elevated sulfur concentrations are known to have extended far beyond this distance\textsuperscript{48,56}, the controlling factor for coating development here has likely been the greater deposition of metal-bearing particulate matter at shorter smelter distances\textsuperscript{20}. Over timespans of decades, rock coatings in the study area are resistant to physical and chemical weathering, and coatings have thus generally remained well preserved in the study area. However, localized physical weathering of coatings has taken place in areas subjected to relatively high levels of pedestrian traffic, and some additional loss of coatings has taken place as a result of the removal or burial of coated bedrock during landscaping and the construction of new buildings and infrastructure (Fig. 3B).

Figure 4. Examples of extensively coated bedrock surfaces near the Horne smelter: (A) glacially smoothed and striated igneous units of mafic to intermediate composition, Rouyn-Pelletier formation (Blake River Group) and associated intrusions; (B) various intrusive and extrusive igneous units of felsic to intermediate composition; (C) rhyolite of the Noranda formation (Blake River Group); (D–F) basaltic and andesitic lava flows of the Rouyn-Pelletier formation; (G,H) Quémont and Joliet rhyolites (Blake River Group). Rock hammer for scale. Site locations are given in Fig. 2.
Collection of Reflectance Spectra of Rock Coatings in the Rouyn-Noranda Study Area. Samples of common types of bedrock in the Rouyn-Noranda region were collected in the study area, with a special emphasis on materials located within ~10 km of the Horne smelter. Coated rock exposures here range from those characterized by prominent and extensive coatings (e.g., Fig. 4) to those with less conspicuous coatings that discontinuously extend across rock surfaces (e.g., Fig. 5A,B). Consistent with a recent field survey 20, distinct rock coatings were not observed in the study area at smelter distances greater than ~6 km (e.g., Fig. 5C–F).

The reflectance spectra of uncoated and coated surfaces of selected rock samples collected within 6 km of the Horne smelter were determined in a controlled lab setting using an Analytical Spectral Devices FieldSpec3 spectroradiometer equipped with a contact probe. The spectral resolution of this system is ~3–12 nm and varies with wavelength. A white Lambertian reference panel was used to calibrate the system on the basis of standard techniques, allowing for the calculation of reflectance ratios based on the electromagnetic radiation reflected off of samples and the reference panel under identical illumination conditions 57.

Reflectance spectra were used to describe the manner in which coatings in the Rouyn-Noranda region reflect incoming radiation at visible, near-infrared, and shortwave infrared wavelengths. Notable associated absorption features were identified and were related to the mineralogical and elemental components of coatings. Comparisons between Rouyn-Noranda spectra and those previously collected in the Sudbury region were performed in order to determine if notable differences exist between the reflectance properties of coatings produced by emissions from the Horne smelter and those of coatings produced in the Sudbury region by the Falconbridge, Coniston, and Copper Cliff smelters 11,12.

Satellite Data and Classification Methodology. Landsat multispectral data have spectral and spatial characteristics that are well suited for surface cover mapping at local and regional scales and for the successful discrimination of a variety of geological classes 58–62. Archived Landsat images are currently available at no cost to users, providing universal access to a large collection of multispectral image databases with extensive geographic and temporal coverage.
This study involved the supervised classification of a surface reflectance database derived from orthorectified and radiometrically calibrated Landsat 8 Operational Land Imager (OLI) data (Fig. 6). Reflectance data were produced by the United States Geological Survey from a cloud-free image acquired for the Rouyn-Noranda region on June 8, 2017 (Landsat Product ID: LC08_L1TP_018026_20170608_20170616_01_T1) using the Landsat 8 Surface Reflectance Code (LaSRC). Utilized reflectance data were derived from OLI bands 2 to 7, covering wavelength ranges within the blue, green, red, near-infrared, and shortwave infrared (Band 2: 452–512 nm; Band 3: 533–590 nm; Band 4: 636–673 nm; Band 5: 851–879 nm; Band 6: 1566–1651 nm; Band 7: 2107–2294 nm). The reflectance database has a uniform pixel size of 30 $\times$ 30 m.

Prior research demonstrated the effectiveness of the maximum likelihood algorithm in the remote-sensing-based identification of coated rock surfaces in the Sudbury region of Ontario, Canada\textsuperscript{11,12}. In that work, the maximum likelihood algorithm, with null class implemented, outperformed a feedforward backpropagation neural network classifier and the Spectral Angle Mapper classifier by consistently producing useful and representative coating maps characterized by low proportions of false positives. Using the Sudbury results as a basis, the present study focused on classification of the Landsat 8 reflectance database using the maximum likelihood classifier.
Among the most widely used routines for supervised classification, the maximum likelihood algorithm parameterizes the ranges of satellite image values that characterize the training sites of particular classes using Gaussian probability distributions derived from associated mean vectors and matrices of covariance. For the utilized version of the maximum likelihood algorithm, the a priori probability of the presence of particular surface classes is assumed to be equal for all classes, and individual pixel labels are assigned to the classes that have the highest associated probabilities. The use of a null class ensures that pixels are only labeled if peak probabilities exceed a threshold, which in the utilized algorithm is defined by a hyperellipsoid with a surface located three standard deviations from the mean vector of any given class. This can improve classification outcomes for e.g. the rock coating class by reducing false positive detections in areas where materials with somewhat similar reflectance characteristics are present (e.g., mine tailings). Though rock coatings were of prime interest in this study, the utilized algorithm requires the specification of a representative and complete list of general surface cover classes. Classifications were produced for the Rouyn-Noranda study area using the following set of classes: coated rock, uncoated rock, uncoated urban materials, uncoated clearings and open pits, predominantly coniferous vegetated sites, predominately deciduous or grassy vegetated sites, deeper water, and shallower or turbid water.

Classification of the Landsat 8 reflectance database allowed for the generation of a map of exposed rock coatings for the Rouyn-Noranda study area. Predicted sites of extensive rock coatings were evaluated in terms of their qualitative consistency with field-based knowledge of the study area gained in this study and in a previous study. Quantitative evaluations of surface cover data were also performed, based on comparison of classification outcomes with test pixels known to be dominated by particular surface cover classes. The numbers of test pixels used in this study were as follows: coated rock (180 test pixels), uncoated rock (288 test pixels), uncoated urban materials (519 test pixels), uncoated clearings and open pits (434 test pixels), predominantly coniferous vegetated sites (349 test pixels), predominately deciduous vegetated sites (391 test pixels), deeper water (168 test pixels) and shallower or turbid water (235 test pixels).

Results

Results generated in this study, including those related to both the spectral characterization of Rouyn-Noranda rock coatings and the generation of a map of prominent rock coatings in the study area, are given below.

Reflectance Properties of Coatings in the Rouyn-Noranda Study Area.

Reflectance spectra of selected coated and uncoated rock surfaces from the Rouyn-Noranda study area are given in Fig. 7a,b. Though typically less than 50 micrometers thick, coatings are generally very effective at masking the spectral characteristics of the underlying rocks. Overall, coated materials have relatively low albedo across the visible, near-infrared, and shortwave infrared. The spectra of coatings are somewhat flat across this range, with typical reflectance values collectively ranging mainly between lows of ~5% at shorter wavelengths and highs of ~16% in the shortwave infrared.

The reflectance spectra of rock coatings in the Rouyn-Noranda study area are characterized by relatively subtle absorption features within the visible-to-shortwave-infrared range. Broad and shallow absorption features near 1000 nm suggest the presence of iron-bearing minerals such as olivine and pyroxene, which are high-temperature minerals expected to comprise some smelter-derived spheroidal clasts embedded within the silica-rich matrix of coatings. Absorption features near 1400 and 1900 nm suggest the presence of water, which is consistent with the expected presence of constituents such as opaline silica as well as hydrous phyllosilicates and sulfates. Features near 2200 and 2350 nm are consistent with the presence of OH-bearing minerals including clays, iron hydroxides, and iron sulfates. Absorption near 2350 nm is also consistent with the presence of carbonates, but minerals of this class are not expected in significant amounts due to the relatively acidic conditions that were present during coating formation. Absorption features such as those near 900, 2200, 2260, 2325, and 2350 nm are consistent with the presence of minerals including sulfates, which are confirmed constituents of some coating surfaces and can also be present within coatings and along the interfaces between coatings and underlying substrates (Fig. 3C,D).

The visible-to-shortwave-infrared reflectance properties of rock coatings in the Rouyn-Noranda study area are very similar to those previously determined for rock coatings in the Sudbury region (Fig. 7c,d), though there is a tendency for some Rouyn-Noranda coatings to have slightly higher reflectance values in the visible and shortwave-infrared ranges than their Sudbury counterparts. Overall, coatings from both Sudbury and Rouyn-Noranda have relatively low reflectance values that increase slightly from the visible into the adjacent infrared. There is a close correspondence between absorption features displayed in both sets of spectra, and this correspondence is consistent with the comparable mineralogical and chemical compositions of coatings from these two areas.

Magnetite and carbon-rich particles are typical products of combustion processes, and should be common components of coatings near both Sudbury and Rouyn-Noranda. These phases commonly generate visible-to-shortwave-infrared spectra of low albedo with few absorption features and may play a role in determining the overall reflectance characteristics of coatings near these two smelting centers.

Discrimination of Rock Coatings Using Landsat 8 Reflectance Data.

Maximum-likelihood classification of the Landsat 8 reflectance database allowed for the generation of a map of extensively and prominently coated bedrock (Fig. 8) that is qualitatively consistent with field experience related to this study and other recent work. In particular, areas of notable bedrock coatings (e.g., Fig. 4) are confirmed to be restricted to smelter distances of less than ~6 kilometers. Prominent coatings are especially concentrated in areas located immediately west, north, and northeast of the Horne smelter. Other areas of notable coating exposure include those located south of Lac Osisko (Figs 2 and 8). In the generated map of coated bedrock, exposures of uncoated bedrock and other uncoated materials (depicted as dark-yellow pixels in Fig. 6D) are appropriately not labeled as coated.
However, the map of coated bedrock problematically does not fully identify areas that are less distinctly coated (e.g., yellow circled areas in Fig. 8), resulting in the underestimation of the total spatial extent of coated or partly coated bedrock. This restricts the map’s utility primarily to the highlighting of the most extensively and thickly coated bedrock exposures in the study area, and to the delineation of areas that were especially affected by past emissions of the Horne smelter.

Overall, 141 of 180 coated bedrock test pixels (78.3%) were correctly identified as such, 19 of 180 coated bedrock test pixels (10.5%) were not classified and were instead assigned to the null class, and only 20 of 180 coated bedrock test pixels (11.1%) were misclassified as uncoated (with 12 of 180 misclassified as uncoated bedrock and 8 of 180 misclassified as uncoated urban) (Table 1). These relatively minor levels of misclassification are not unexpected, as there is a continuum of coating extent (from 100% cover to negligible or absent cover) that necessarily requires that some areas described as coated by observers on the ground may be insufficiently distinct to be properly identified as coated by a classifier working with relatively large pixels (30×30 m). Misclassified coated pixels are associated with materials with reflectance properties that are either similar to those of coatings (e.g., some uncoated urban materials) or that grade from coated bedrock to other related classes (e.g., uncoated bedrock). In the classification of Landsat 8 reflectance data, none of the test pixels for the seven other classes were misclassified as coated, confirming that false positives are uncommon for the coated bedrock class.

A higher proportion of coated or partly coated exposures of bedrock was successfully identified in a maximum likelihood classification performed without the null class (Fig. 9). Specifically, 163 of 180 coated bedrock test pixels (90.5%) were correctly identified as such, and 17 of 180 coated bedrock test pixels (9.4%) misclassified as uncoated (with 13 of 180 misclassified as uncoated bedrock and 4 of 180 misclassified as uncoated urban) (Table 1). However, the absence of a null class allowed pixels to be labeled without a minimum probability
threshold, which permitted labels to be assigned under circumstances in which single classes were not strongly favored with high estimated probabilities. In the generated database, confusion between the coated bedrock class and spectrally similar classes (e.g., geological materials in tailings ponds) was correspondingly increased, and the proportion of false positives for the coated bedrock class was also increased, reducing the utility of this database relative to that generated through the implementation of a null class. Though only 1 of 255 shallow water test pixels (0.4%) and 1 of 519 uncoated urban test pixels (0.2%) were misclassified as coated bedrock in the classification conducted without a null class, 14 of 288 uncoated bedrock test pixels (4.9%) were more problematically misclassified as coated bedrock, underscoring the reduced confidence with which the associated map can be used to identify coated sites in the Rouyn-Noranda study area. False positives can be especially problematic since they can in some instances wrongly suggest that coated bedrock is present in areas where no coatings exist at all, whereas false negatives have a tendency to nevertheless be proximal to sites correctly identified as coated, and thus tend to have much less of a negative impact on the overall visual impression of the predicted spatial distribution of coatings.

Figure 8. Spatial distribution of the most prominently coated bedrock exposures (red) in the Rouyn-Noranda study area (Fig. 2), as generated by a maximum likelihood classifier with a null class (overlaid on reflectance data derived from OLI Band 5, acquired in the near infrared). This database successfully identifies areas that are notably characterized by the presence of distinct coatings, with a low proportion of false positives, and provides a good overview of the general spatial distribution of coated bedrock in the Rouyn-Noranda study area. However, the database does not fully identify areas containing less distinctly or less extensively coated bedrock; selected sites where partially coated bedrock exists but was not discriminated by the classifier are identified by yellow circles. Image at right is an enlargement of the area outlined in yellow at left. Image classification and processing were performed using Geomatica software.

|             | coated rock correctly classified | coated rock misclassified as uncoated rock | coated rock misclassified as uncoated urban | coated rock assigned to null class |
|-------------|---------------------------------|------------------------------------------|--------------------------------------------|----------------------------------|
| (A) With Null Class | 78.3%                           | 6.7%                                     | 4.4%                                       | 10.5%                            |
| (B) Without Null Class | 90.5%                           | 7.2%                                     | 2.2%                                       | n/a                              |

Table 1. Summary of maximum likelihood results for classifications with a null class (A) and without a null class (B). Classes mislabelled as coated bedrock for the classification with a null class: none. Classes mislabelled as coated bedrock for the classification without a null class: uncoated bedrock (4.9%), shallower water (0.4%), uncoated urban (0.2%). Though the classification without a null class has a higher proportion of coated bedrock test pixels that were correctly classified as such, it is also characterized by problematic false positives involving other classes, most notably the uncoated bedrock class.
Discussion

The reflectance spectra of Rouyn-Noranda rock coatings have properties that are comparable to those previously measured in the Sudbury region, which is consistent with associated similarities in mineralogical and elemental compositions. Coatings near both Rouyn-Noranda and Sudbury tend to have relatively flat reflectance spectra, involving overall reflectance values of roughly 5 to 15% across the visible, near-infrared, and shortwave infrared. Both sets of spectra are characterized by subtle absorption features consistent with the presence of known or likely components including opaline silica, hydrous clays, sulfates, carbon-rich particulates, and high-temperature oxides and silicates. Though notable similarities can exist between the spectra of rock coatings and those of materials including mine tailings, the most prominently coated bedrock surfaces in the Rouyn-Noranda study area were successfully discriminated from other surface classes through the supervised classification of reflectance data derived from Landsat OLI data. Less prominently coated surfaces were not identified in all cases. As previously determined for the Sudbury region, the use of a null class greatly reduces the occurrence of false positives in maps depicting the spatial distribution of coated rock, improving the utility of associated databases despite the lower proportion of correctly identified sites of coated bedrock.

The mapped extent of prominent rock coatings depicted in Fig. 8 is representative of the time frame in which image data were acquired (i.e., June, 2017), and is limited to sites where coatings remained well preserved and well exposed at that time. The mapped extent of prominent coatings generated using the Landsat 8 reflectance database does not include areas where coatings may have once existed but later became extensively weathered, vegetated, or buried (e.g., Fig. 3B). The mapped extent of coatings also does not include areas where the effects of smelter emissions may have been severe but where the absence of an appropriate rock substrate prevented the formation of coatings (e.g., areas mantled by glaciofluvial sediments). Given these considerations, the mapped extent of coatings should mainly be utilized as a general guide regarding the approximate smelter distances within which the combined effects of acid rain and the deposition of smelter particulates were greatest.

A total of 1287 pixel locations are predicted to have been associated with well-exposed fully or partly coated bedrock in the Rouyn-Noranda study area in 2017. With pixel areas of 30 × 30 m (=900 m²), this gives a total predicted surface area of 1,158,300 m², or ~1.2 km². A classification success rate of 78% for the coated bedrock class (Section 7.2) implies a current total surface area of rock coatings of ~1.5 km². Though notable, the spatial extent of prominent dark coatings in the Rouyn-Noranda study area is only roughly 1% of that which characterizes the Sudbury region, where emissions from historical roast yards and three major smelting centers prior to...
the mid-1970s produced a total surface area of exposed rock coatings that is estimated for the year 2000 to have been as great as ~155 km².

Lichen cover can be significant on bedrock in the Rouyn-Noranda study area, and, where extensive, can reduce the effectiveness of remote sensing techniques in the successful discrimination of associated geological classes. However, there is a general tendency in the study area for coated bedrock surfaces to be characterized by much lower amounts of lichen cover than uncoated surfaces. Since the reflectance characteristics of lichens can differ considerably from those of bedrock, the greater tendency for lichens to colonize uncoated bedrock may assist in the discrimination of coated bedrock from uncoated bedrock by further increasing the spectral separation between these classes.

This study utilized Landsat 8 data characterized by a relatively coarse pixel size of 30 × 30 m. Improved outcomes in the discrimination of rock coatings may be possible, especially where coatings are notably discontinuous and irregularly distributed, through the use of image databases with higher spatial resolutions. In such areas, smaller pixel sizes may increase the abundance of relatively pure pixels (i.e., individual pixel locations dominated by single classes), possibly providing a clearer basis for discrimination of the coated class. Improved classification outcomes may also result from the use of hyperspectral rather than multispectral image databases, since differences in the reflectance properties of the coated class and certain uncoated classes (e.g., mine tailings and asphalt) can be subtle and are less likely to be consistently detectable using image databases with poorer spectral characteristics.

Classification results for the Rouyn-Noranda study area confirm that multispectral datasets can be used to detect and map prominent rock coatings near smelters, highlighting the overall spatial distribution of sites previously subjected to severe levels of acid rain and smelter-derived particulates. Remote sensing techniques should be applicable to the study of the spatial distribution of rock coatings near Rouyn-Noranda, including sites where environmental conditions are sufficiently severe for the development of rock coatings to be ongoing. For example, a time series of maps of rock coatings could potentially be used to better understand the spatial distribution of ongoing environmental degradation in the vicinities of smelters that are actively emitting high levels of particulates, heavy metals, and sulfur dioxide. Remote sensing techniques may similarly prove useful in the monitoring of environmental recovery where smelter emissions have been reduced or eliminated, by facilitating the generation of maps that depict the progressive reduction of exposed coatings as a result of weathering and erosion, revegetation, and the construction of roads and other infrastructure.

Conclusions

1. Prior to the mid-1970s, development of rock coatings was promoted in the Rouyn-Noranda region by emissions of particulates and sulfur dioxide from the Horne smelter. Though typically less than 50 micrometers thick, these coatings are generally very effective at masking the reflectance characteristics of rock substrates.

2. Overall, coatings are similar in composition to those previously investigated in the Sudbury region, and correspondingly have similar spectral characteristics. Rock coatings in the Rouyn-Noranda region have relatively low albedo across the visible, near-infrared, and shortwave infrared, and associated reflectance spectra are characterized by subtle absorption features that are consistent with the known or expected presence of constituents including opaline silica, olivine, pyroxene, hydrous phyllosilicates, and sulfates.

3. Classification of a reflectance database derived from Landsat 8 OLI data successfully produced a map of prominently coated bedrock in the Rouyn-Noranda region. This map does not identify all areas that are less distinctly coated, and thus underestimates the total spatial extent of coated bedrock here. Detection of additional exposures of coated bedrock could not be performed without increasing confusion between coated bedrock and uncoated materials such as mine tailings.

4. The total surface area of rock coatings near Rouyn-Noranda is estimated to currently be ~1.5 km², nearly all of which is located within ~6 km of the Horne smelter.

5. Improved outcomes in the discrimination between rock coatings and other classes may be possible through the use of image databases with higher spatial resolutions and/or enhanced spectral characteristics.

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Author Contributions

David Leverington conducted field work and sample collection, photographed field sites, generated reflectance spectra, processed and classified satellite images, prepared manuscript figures, and wrote the initial manuscript. Michael Schindler conducted field work and sample collection, characterized the mineralogy and geochemistry of samples, generated SEM images, and participated in revision of the manuscript.

Additional Information

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