AIRBORNE MAPPING OF VEGETATION CHANGES IN RECLAIMED AREAS AT HIGHLAND VALLEY BETWEEN 2001 AND 2008

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ABSTRACT

The remote sensing program at Highland Valley Copper provides maps of vegetation for the entire mine site that extend the more detailed but sparse *in situ* sampling. A unique and growing time series for 7 of the 8 years between 2001 and 2008 allows us to examine vegetation trends over time with good spatial detail. We are able to map areas with similar vegetation types and/or similar histories, and in particular, to identify that attaining reclamation success and those requiring additional attention in order to achieve that state. The resulting maps provide a detailed synopsis of the vegetation trends helpful to reclamation managers. In this study we examine more closely the statistically significant correlation observed between precipitation and remotely sensed vegetation cover at many of the reclamation sites. Analysis suggests that the strength and time scale of the correlation is related to site slope. This is important for site management because it identifies the particular locations most likely to benefit from water retention measures. We also demonstrate the removal of the precipitation-related signal from the remote sensing data in order to derive more desiccation-independent estimates of biomass. We hope to eventually extend this analysis to the entire imaged area and, if successful, incorporate it into our standard analytical protocol.

Keywords: reclamation, vegetation cover, change, remote sensing, water retention

INTRODUCTION

Highland Valley Copper is a large, open pit copper mining complex, situated between 1200 and 1600 m above sea level on the Thompson Plateau, near the town of Logan Lake, British Columbia, 220 km northeast of Vancouver and 55 km southwest of Kamloops. It consists of four mining operations: Lornex, Valley, Bethlehem and Highmont. Operations at the latter two were discontinued in the mid-1980s and decommissioning begun. Production is currently planned to cease in 2019. The total disturbed area is currently 6200 ha.

Reclamation is an integral part of production and decommissioning. Reclamation monitoring programs are conducted annually at Highland Valley to assess the progress toward achieving the end land use objectives, and to determine when individual sites achieve a self-sustaining state. Since 2001, we have been developing remote sensing tools for improving the efficiency and effectiveness of the monitoring program (Richards *et al*., 2003; Richards *et al*, 2004; Borstad *et al*, 2005).

Over the years, different analytical techniques have been applied to map the growth of forage crop plantings, including multispectral classification to monitor the success of grasses versus legumes, and the use of spectral indices to remotely estimate vegetation biomass. A calibration of the NDVI remote sensing index (Normalized Difference Vegetation Index) to biomass has been determined for the Highland Valley site; however this index is sensitive to the physiological condition of the vegetation. Although this information is in itself useful for evaluating vegetation condition, it is also desirable to obtain biomass estimates that are independent of the vegetation's greenness, since the current standards for reclamation success are expressed in terms of sustainable biomass. This paper describes the use of NDVI to assess both the susceptibility of sites undergoing reclamation to desiccation, as well as their overall reclamation status in terms of longer-term trends in biomass.

METHODS

1.1 Airborne and Ground Data

Data acquisition methodology has been previously described (Richards *et al*., 2003; 2004; Borstad *et al*, 2005) and will not be repeated in detail here. In all years between 2001 and 2008 except 2004, airborne multispectral imagery was acquired in July using a Compact Airborne Spectrographic Imager (CASI), configured to acquire imagery in 9 spectral bands, and with 2.5m ground sampling distance. The imagery is radiometrically calibrated and mapped to coordinates consistent with the mine Geographic Information System (Mine Units) with an estimated geographic accuracy of ±10m.

1.2 Airborne Data Analysis

The Normalized Difference Vegetation Index (NDVI) was calculated from the red and near infrared spectral bands of the 2001-2008 CASI imagery as:

$$NDVI = (R_{776} - R_{665}) / (R_{776} + R_{665})$$

where R_λ = at-sensor radiance at wavelength λ (in nanometres). In 2005, we developed a curvilinear NDVI calibration based on *in situ* biomass measurements made by C.E. Jones & Associates in 2003:

$$\text{RS biomass} = b*(NDVI-c)/(a-NDVI+c)$$

where a=1.355, b=6958.7, c=0.129. We refer to the NDVI derived estimates as Remote Sensing (RS) biomass in order to distinguish it from *in situ* measurements.

1.3 Precipitation Response

The *in situ* reclamation monitoring program instituted at Highland Valley Copper for forage seeded sites comprises two sets of standardized assessments, the first conducted two years following seeding and the second four to five years later. A third assessment is performed three or more years after that in order to establish reclamation success. Fertilizing of the sites is carried out for up to four years following seeding, depending on the site material (waste rock, tailings and/or biosolids).

Our remote sensing analysis was applied to the 14 sites undergoing third assessments in 2005. For those sites the mean NDVI was extracted from the annual CASI imagery using site boundaries defined by Highland Valley, beginning with the year following the last application of fertilizer. The extracted NDVI time series were then compared with total precipitation recorded at the Lornex weather station for the 10, 20, 30 or 60 days preceding each year's image acquisition flight. Third assessment sites were selected for analysis because they were known to have been at least 9 years old (from seeding) in 2005, and were unlikely to have been disturbed or otherwise treated over the course of the NDVI time series in such a way as to invalidate the analysis.

RESULTS

1.4 Precipitation Response

Figure 1 and Table 1 summarize the responsiveness of NDVI at the third assessment sites to precipitation in the 10, 20, 30 or 60 days prior to image acquisition. Nine of the 14 areas evaluated displayed a significant relationship between NDVI and precipitation at some temporal scale. Only 5 areas showed no significant relationship.

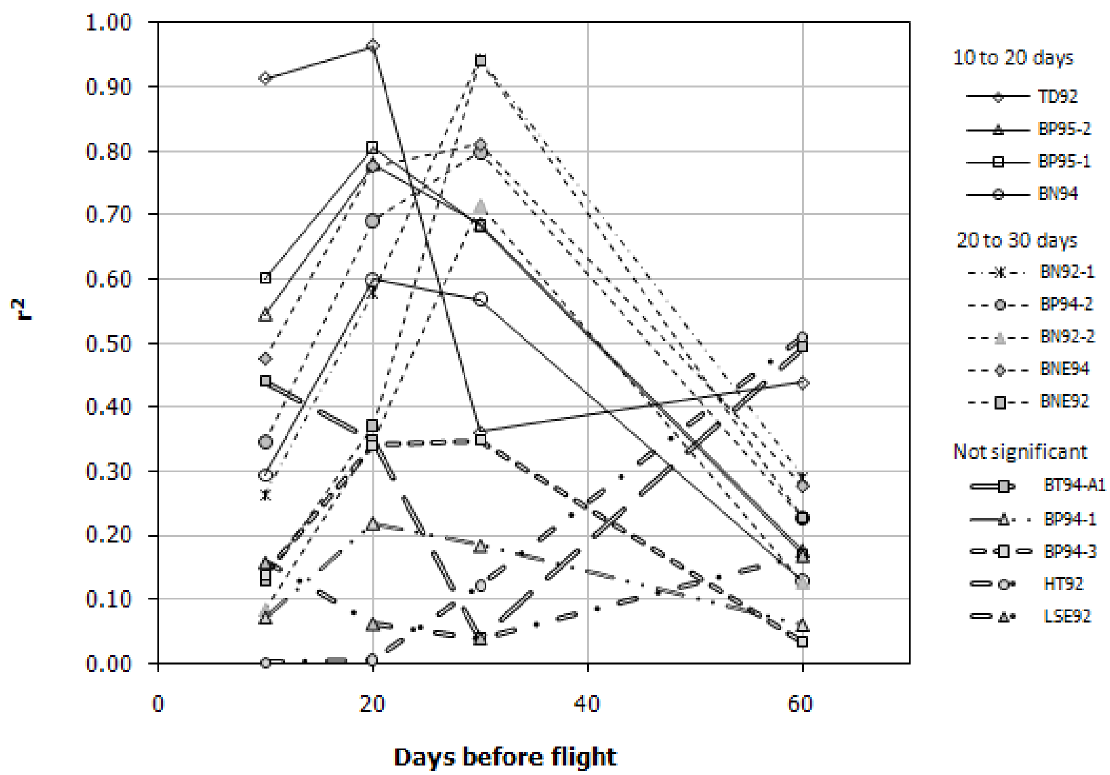

Figure 1. Strength of the NDVI response to precipitation (expressed as r^2), as a function of the number of days accumulated precipitation before image acquisition. Each plot represents one site.

Areas showing no relationship between NDVI and precipitation: The 5 sites showing no significant relationship to precipitation were examined individually to determine their reclamation status. Their NDVI time series are shown in Figure 2.

<u>Bethlehem Tailings area 1 site BT94-A1</u> exhibited reasonably stable NDVI until 2006, but there was a sudden decline in 2007 and 2008. The imagery for this site (Figure 3) shows that the declines in 2007 and 2008 were due to the intentional clearing of portions of the area, so that apart from these disturbances the area was in fact stable and could be considered successfully reclaimed.

<u>Bethlehem Plant sites BP94-1 and BP94-3</u> both showed general declines over time, although there was a slight improvement in 2008 over 2007 at both locations (Figure 2). The overall NDVI at BP94-1 was higher than at BP94-3, so it could be considered in better overall condition, but the decline independent of precipitation could be cause for concern in both areas. In the absence of additional information, an examination of the imagery suggests that the declines were natural and not due to human disturbance as occurred at Bethlehem Tailings. Subarea BP94-2 showed a significant relationship with precipitation within 30 days of the CASI flight (Table 1), but if the precipitation-related portion of the signal is disregarded, this area also showed declines similar to BP94-1 and BP94-3.

Table 1. Grouping of third assessment sites according to their precipitation responses.

NDVI vs precipitation	Area	P value
never significant at p=0.05	Bethlehem Tailings Area 1 BT94-A1	Not significant
	Bethlehem Plant site BP94-1	Not significant
	Bethlehem Plant site BP94-3	Not significant
	Highmont Tailings HT92	Not significant
	Lornex SE LSE92	Not significant
Strongest relationship with cumulative precipitation 0-10 days before flight	No areas (but Trojan Dam TD92)	p<0.001
Strongest relationship with cumulative precipitation 0-20 days before flight	Trojan Dam TD92	<0.0001
	Bethlehem Plant site BP95-2	<0.01
	Bethlehem Plant site BP95-1	<0.01
	Bethlehem North BN94	<0.05
	Bethlehem Plant site BP94-1	Not significant
Strongest relationship with cumulative precipitation 0-30 days before flight	Bethlehem North BN92-1	p<0.001
	Bethlehem NE BNE92	p<0.001
	Bethlehem NE BNE94	p<0.01
	Bethlehem Plant site BP94-2	p<0.01
	Bethlehem North BN92-2	p<0.05
	Bethlehem Plant site BP94-3	(Not Significant, lowest p similar for 20-30 days)
Strongest relationship with cumulative precipitation 0-60 days before flight	Highmont Tailings HT92	Not significant

Highmont Tailings HT92 and Lornex Southeast LSE92 both showed broad increases in NDVI over time, Highmont a little more strongly than Lornex (Figure 2), so could be considered self-sustaining, although the wide error bars on Lornex suggest considerable within-site variability. Highmont showed some susceptibility to drying after 60 days (i.e., the highest r^2 was to 60-day precipitation) but the relationship was not statistically significant (Figure 1 and Table 1).

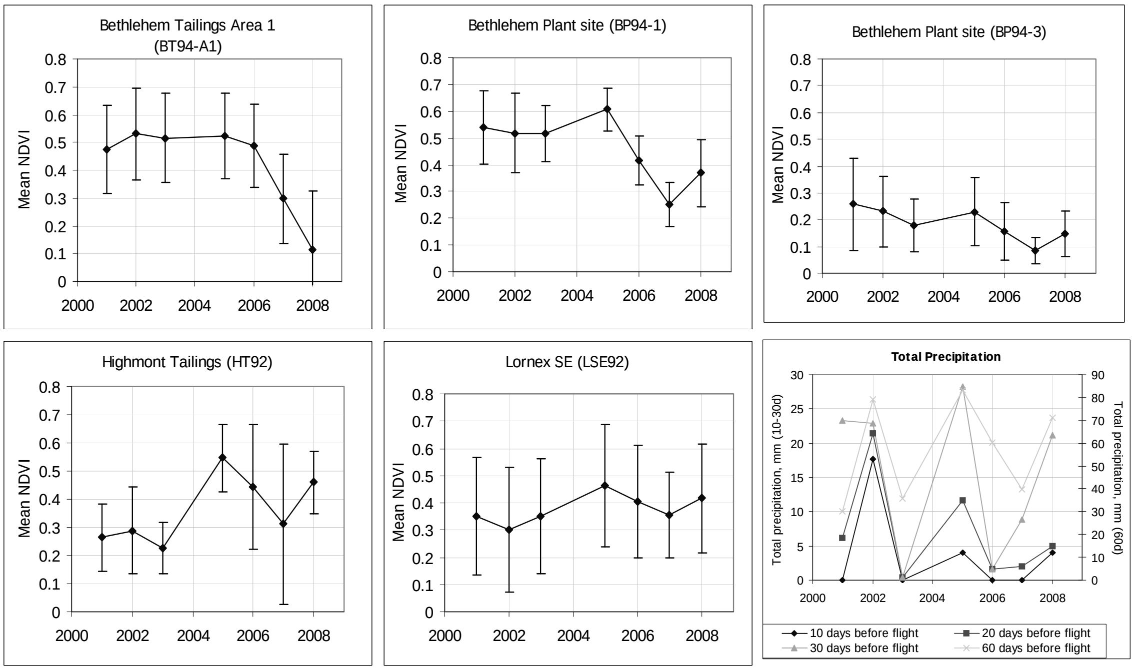

Figure 2. NDVI time series for sites showing no significant relationship with precipitation (error bars indicate ±1 standard deviation for each site). The last plot shows time series of cumulative precipitation for 10, 20, 30 or 60 days prior to image acquisition.

Areas with NDVI correlated with precipitation: The remaining nine third assessment sites all showed statistically significant relationships between NDVI and precipitation, with varying response times. Trojan Dam (TD92) showed the shortest response, with strong significant relationships with precipitation both 10 days (r^2 = 0.91, p<0.001) and 20 days (r^2 = 0.96, p<0.0001) prior to the survey flight. For the remaining 8 sites NDVI correlated with 20- to 30-day precipitation (Figure 1 and Table 1).

We suggest that the timing of the response to precipitation gives an indication of the rate of water loss in each location: sites showing the shortest response dry out the most quickly while those showing a longer response are likely able to retain water longer. Using ground observations made by C.E. Jones & Associates in 2005, we examined some of the site properties that could affect water retention, including substrate material, slope and elevation (Table 2). In general, sites that displayed the shortest response times were the most sloped, while those showing no correlation to precipitation were the least sloped. The one exception to the trend was site BP95 (Bethlehem Plant site, seeded 1995) that showed a relatively strong, short precipitation response in an area with a mean slope of 0°. Overall, there did not appear to be any relationship with substrate material or elevation, although we caution that the number of sites included in this assessment was small (a total of 10 sites with both precipitation analysis and site information). We did not examine slope direction or aspect. A more detailed analysis of the relationship between NDVI and slope and aspect could be performed using a mine Digital Elevation Model. The inference with respect to site remediation is that water loss would be most likely ameliorated using measures to reduce slope, for example terracing or cross-slope (as opposed to down-slope) furrowing.

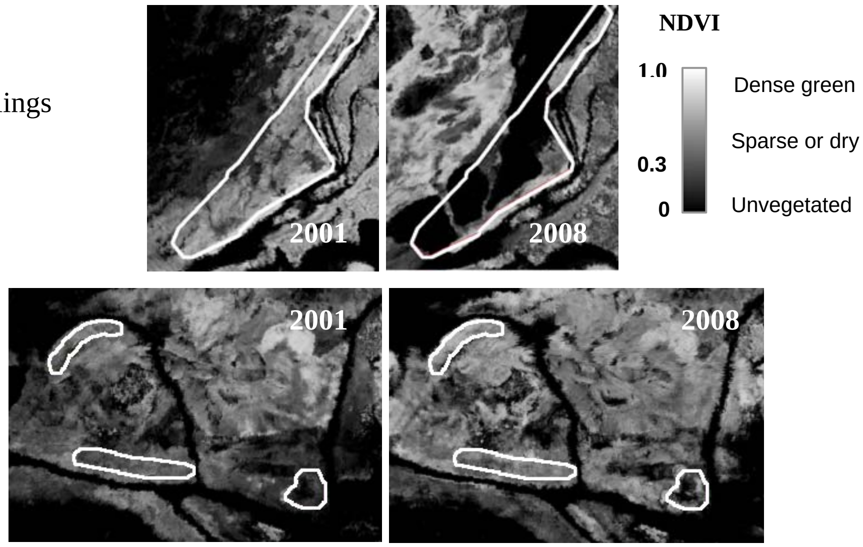

Figure 3. NDVI imagery from 2001 and 2008 at Bethlehem Tailings and Bethlehem Plant site, showing intentional clearing of vegetation at the former versus more natural declines at the latter.

1.5 Removal of Precipitation Signal

For sites subject to desiccation (i.e., where NDVI was correlated with precipitation), the precipitation signal was mathematically ‘removed’ from the NDVI time series, in order to better evaluate reclamation success. Precipitation-corrected time series (Figure 4c) were calculated by adding the residual of the NDVI vs precipitation linear trend (Figure 4b) to the temporal mean (Figure 4a) for each site.

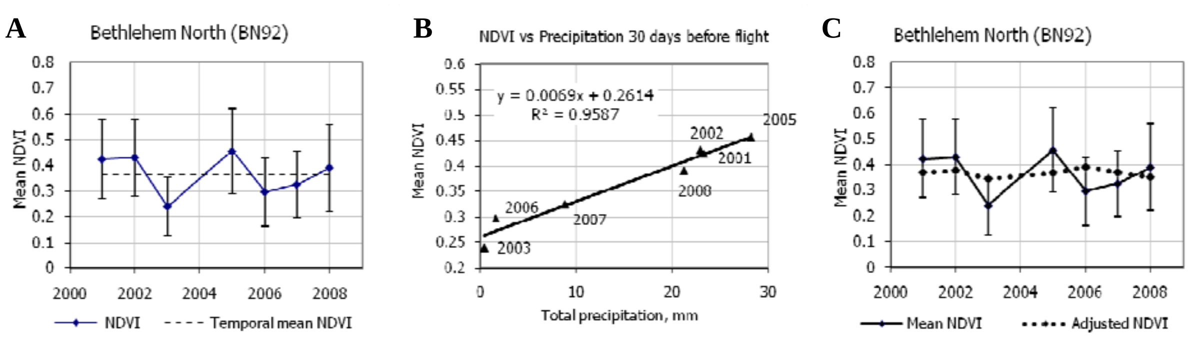

Figure 4. Calculation of precipitation-corrected NDVI time.

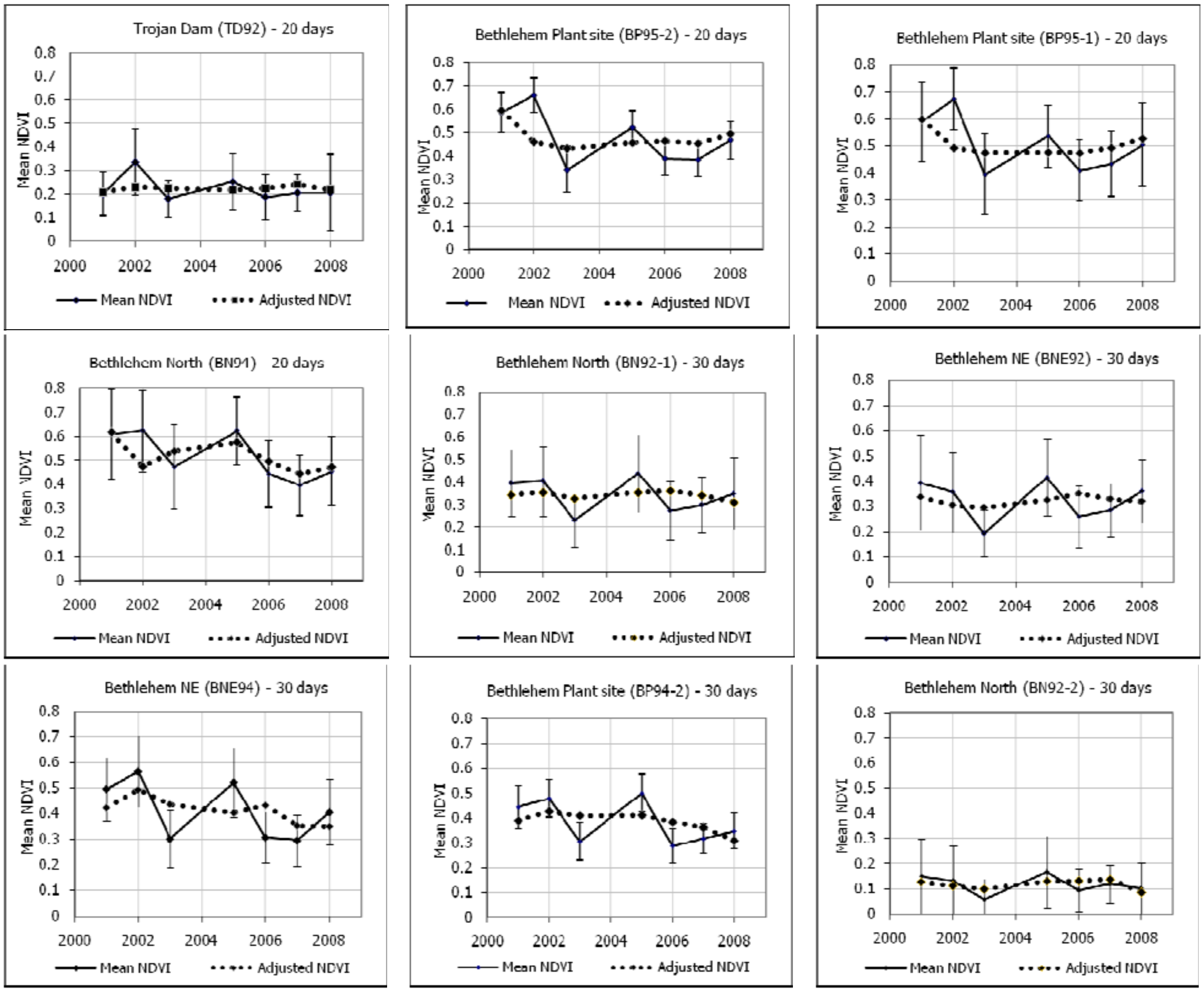

Figure 5. NDVI time series for sites showing a statistically significant relationship with precipitation, and NDVI adjusted based on precipitation in the preceding 20 or 30 days. Error bars on the original NDVI time series indicate ±1 standard deviation variability within each site.

Figure 5 shows both the original and adjusted time series for each site. The adjusted NDVI time series shows that many of the desiccation sensitive sites exhibited little or no real change over the 8-year period between 2001 and 2008. Apart from precipitation-related variation, we infer:

- Trojan Dam and Bethlehem North site BN92-2 vegetation remained relatively constant and sparse (low NDVI), with adjusted NDVI near 0.22 (equivalent to RS biomass of approximately 520 kg/ha) at Trojan, and near NDVI = 0.1 (biomass near 0) at BN92-2.

- Bethlehem North site BN92-1 and Bethlehem Northeast (BNE92) also remained relatively stable but with more vegetation, in the range NDVI = 0.30-0.36, or RS biomass ~1000-1400 kg/ha.

- Sites BN94, BNE94 and BP94-2 all showed broad declines over time. By 2008, while the adjusted NDVI at BN94 remained above 0.37 (approximately equivalent to the reclamation threshold of 1500 kg/ha), at BNE94 and BP94-2 the adjusted NDVIs had fallen slightly below this threshold.

- Bethlehem Plant site BP95-1 and BP95-2 showed initial decreases in NDVI, but both show more recent signs of real growth. The overall vegetation density at both has remained relatively high, despite these changes.

Table 2. Comparison of desiccation susceptibility, expressed as the timing of maximum correlation to precipitation, with site properties, including substrate material, elevation and slope, as measured at ground survey locations by C.E. Jones & Associates during their 2005 third assessments. Sites are listed in order of decreasing susceptibility to desiccation. p = level of significance, NS = not statistically significant.

Site	**Location**	**Seed Year**	**Timing of maximum correlation (days)**	**Probability**	**Material**	**Elevation (m)**	**# plots**	**Slope °**		
								Min	Max	Mean
Trojan Dam	TD92	1992	10-20d	<0.001	Till/waste rock	1400	66	0	32	15
Bethlehem North	BN94	1994	20d	<0.05	Till	1500-1600	4	6	18	11
Bethlehem Plant site	BP95	1995	20d	<0.01	Till/waste rock	1540	2	0	0	0
Bethlehem North	BN92-1	1992	30d	<0.001	Till/waste rock	1537	25	0	22	6
	BN92-2	1992	30d	<0.05						
Bethlehem Northeast	BNE92	1992	30d	<0.001	Till/waste rock	1565	31	0	25	8
Bethlehem Northeast	BNE94	1994	30d	<0.01	Till	1500-1600	19	0	20	6
Bethlehem Plant site	BP94-2	1994	30d	<0.01	Till	1500-1600	8	0	20	8
	BP94-1, BP94-3	1994		NS						
Highmont Tailings	HT92	1992	60d	NS	Tailings	1480	22	0	0	0
Bethlehem Tailings	BT94-A1	1994		NS	Tailings	1472	26	0	0	0
Lornex Southeast	LSE92	1992		NS	Waste rock	1580	38	0	14	3

Figure 6 shows that the precipitation-adjusted RS biomass estimates compare favourably with available *in situ* measurements. Four of the data points shown represent sites where NDVI was not significantly correlated with precipitation and hence no adjustment was made. In the remaining data, some of the scatter appears to have been reduced by the precipitation adjustment, although BN94 (sampled in 2005) and BP95-1 (sampled in 2001, circled points in Figure 6) lie well off the 1:1 relationship (dashed line), and BNE94 (sampled in 2001), which originally was well predicted was underestimated after adjustment. The reasons underlying these outliers have not been explored.

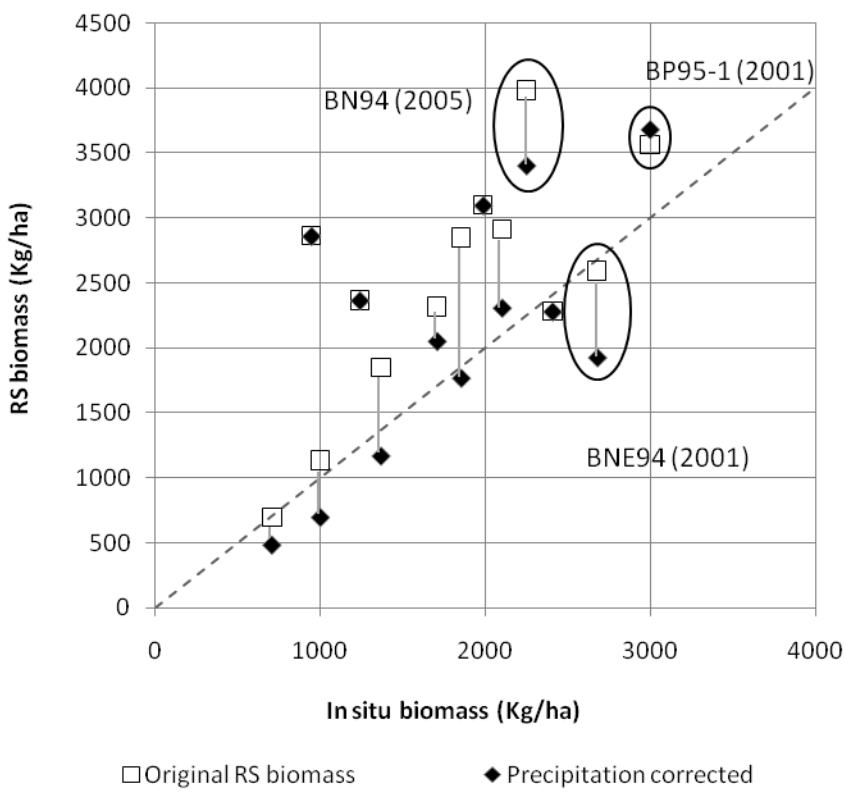

Figure 6. Comparison of *in situ* biomass and remote sensing estimates based on the original NDVI values (open squares) and on values adjusted to remove the effects of precipitation (diamonds). The dashed line represents 1:1. Circles and labels identify outlier sites and the year in which biomass was measured.

CONCLUSIONS

Our examination of the precipitation-related signal present in NDVI suggests that it can be used to quantify susceptibility to desiccation on a site-by-site basis, expressed as the time response to precipitation, and that in general this susceptibility appears to be most strongly related to site slope, and less to other factors such as elevation or substrate material. These inferences are based on a relatively small sample of 10 third assessment sites and the assumption that precipitation is uniform across the mine site. In order to refine our interpretation, it would be beneficial to extend the analysis beyond 10 sites and to include more parameters. With a larger sample size and additional parameters such as site aspect, additional relationships may become evident. The relationship between NDVI and precipitation could also be explored at the image scale, producing maps of desiccation susceptibility on a pixel-by-pixel basis. These could then be compared with a Digital Elevation Model and material maps, for example, to verify or refine the findings we have presented here. The effectiveness of measures to reduce desiccation susceptibility could also be assessed using the same approach we have used here, although several years' data post-treatment would be required to properly ascertain the successfulness of the measures.

For the assessment of long-term reclamation success, our demonstration also suggests that the precipitation-correlated portion of the NDVI signal can be removed, to produce more easily interpretable time series. As above, this analysis has thus far been applied to a selection of third assessment sites only, but could as well be applied across the entire mine site. In order to perform such an analysis in a meaningful way, it would be important to obtain maps of treatment schedules (dates of disturbances, seeding, fertilization and so on), so that the analysis could be applied over time frames appropriate for each area.

These new analytical tools can be added to our existing suite of algorithms (biomass and desiccation indices, spectral and temporal classification), to position managers to better understand the progress being made at each reclamation site, and to pinpoint areas requiring additional remedial treatment.

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