Using Landsat Images To Map Quality And Quantity Sugar Beet Yield.

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On a large scale, such as the Red River Valley (RRV), the primary factor that determines beet yield is climate during the growing season, while on a small scale, such as a family farm, growers use different farming practices to maximize economic returns. It is important for the industry as well as the growers to be able to predict sugar beet yield and sugar content on a farm or even a field scale, so that they can optimize economic returns by adjusting the harvest schedule.

Landsat imagery with a 30 m ground resolution and 12100 square miles coverage can provide synoptic mapping for the entire RRV, while detecting in-field variability. It is desirable to be able to use Landsat to predict beet yield and sugar content. To evaluate this feasibility, we have acquired 15 scenes of Landsat imagery during the 2002-2003 growing seasons, and measured fresh beet weight (BW, t acre^{-1}) and fresh matter sugar content (SC, g g^{-1}) in four different fields. For the year of 2003, we also collected hyperspectral reflectance on the ground in two of the experiment fields.

From the hyperspectral measurements, we found positive correlations (~0.65) between the reflectance in the NIR wavelengths and the beet weight. It is well known that NIR reflectance is related to crop productivity. After comparing various indices, we found that the Enhanced Vegetation Index (EVI) best captures the variability in beet weight.

Similarly, SC inversely correlates with the mid-infrared reflectance. We developed an index applicable to the Landsat sensor, NVI52 = (band 5 - band 2) / (band 5 + band 2). We chose these two bands because band 5 is sensitive to the leaf moisture and band 2 measures the greenness of the canopy.

We evaluated these two indices using Landsat images for both 2002 and 2003 and the results suggest that these indices have potential to be used to predict the beet weight and the sugar content. However, to further improve the predictability, we will integrate information from other data sources such as soil type, rainfall, air temperature, leaf evaporation and solar radiation during the growing season.

1. Introduction

It is well known that sugar beet yield is determined by a variety of factors including weather conditions, vegetation growth, soil characteristics, and even farming practices such as sowing dates or plant densities (Bouman 1992; Guerif and Duke 1998; Werker and Jaggard 1998; Richter et al. 2001). Using remote sensing derived vegetation index, which approximately correlates with vegetation productivity, researchers were able to monitor the ongoing growth of sugar beet and to predict beet yield (expressed as beet weight, BW, t ac^{-1}) over a large spatial scale (Clevers 1997; Guerif and Duke 1998; Guerif and Duke 2000). Since the net sugar production also depends on the yield quality, expressed as fresh matter sugar content (SC, g g^{-1}), it is becoming desirable to be able to predict both quantity and quality of sugar beet (Vandendriessche 2000a).

While the total yield of sugar beet is related directly to productivity, the sugar beet quality, i.e., the percentage of sugar content, is affected by climate and soil conditions. Previous studies found that SC is impacted, in general, by the temperature of soil and air, the availability of nitrogen and water, and solar radiation (Webb et al. 1997; Demmers-derks et al. 1998; Werker et al. 1999; Wiesler et al. 2002). Vandendriessche (Vandendriessche 2000b) indicated, however, that SC varies significantly from season to season and from place to place, and is very difficult to estimate.

This research focused on developing prediction models using remote sensing data for both BW and SC of the sugar beet in the Red River Valley, which hosts one the of largest non-irrigated sugar beet field in US (Leff et al. 2004). For two years from 2002 – 2003, we had recorded hyperspectral reflectance of sugar beets at various growing stages and measured the sugar beet yield and content at harvest in 4 different fields. We also collected Landsat scenes over the same time period. In the following, we briefly described the data we have collected. Then we presented in detail the analysis of the data to develop the spectral indices that are most sensitive to BW and SC. Moreover we evaluated the spectral prediction model with Landsat data to determine the temporal frame within which the prediction is the most reliable. And finally we discussed the limitations of the models and the possible improvements.

2. Data

We collected ground data in 4 different fields, 2 during the 2002 growing season and other 2 during 2003 season (Figure 1-a). For each field, we picked 9 to 14 sites according to the management zones. And for each site, we took 2-3 samples and averaged them to produce one measurement. This is to minimized random sampling errors when comparing with Landsat data, whose pixel coverage is ~30x30 m^2. Figure 1-b shows an example of our sampling strategy.

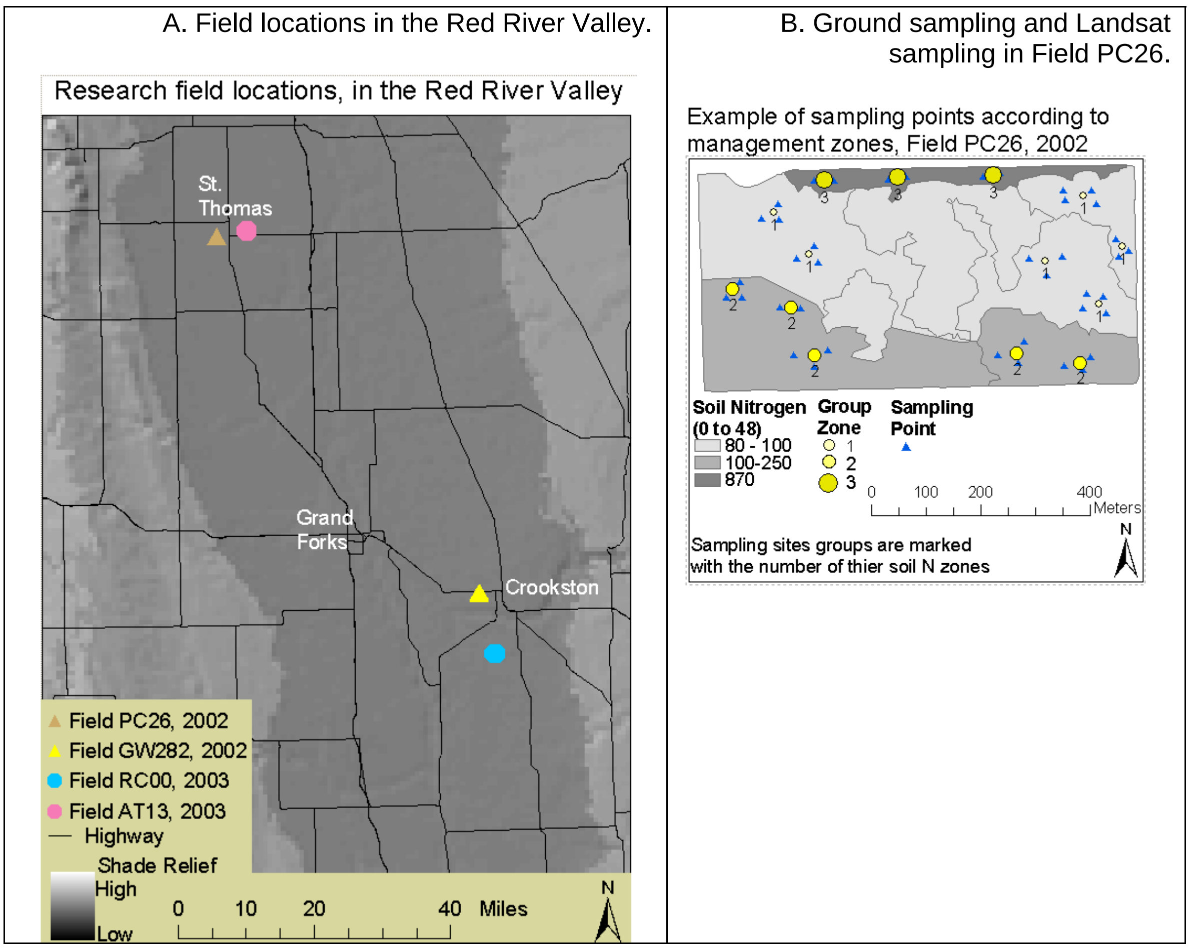

Figure 1 Ground sampling sites.

We measured hyperspectral reflectance from 350 – 2500 nm using ASD spectroradiometer (ASD Instruments, Boulder, CO) from 1.5 meter above the canopy in mid-August, end-August and mid-September, respectively, during 2002 and 2003 experiments. All the measurements were taken before noontime to minimize the effects of water stress and leaf angle (Danson and Aldakheel 2000). To further reduce the random errors, we took 10 ASD measurements continuously and used the average as representative for that measurement point. Unfortunately, the instrument was not correctly calibrated during the 2002 campaign and therefore only 2003 hyperspectral data were used. To simulate the reflectance that would be recorded by the Landsat sensors, we convolved the hyperspectral signatures with the spectral responses of each of Landsat multi-spectral bands (Jacquemoud et al. 1995; Liang et al. 2002).

At the end of each growing season, we harvested sugar beets at each site, which were then analyzed at the laboratory of American Crystal Sugar Inc. for beet weight (BW) and fresh matter sugar content (SC).

We acquired 8 scenes from Landsat 7 ETM+ for the year 2002 experiment and 7 scenes from Landsat 5 TM for 2003 because an irreparable problem with the Scan Line Corrector on the Landsat 7 spacecraft, noticed in May 2003, limits the usability of data only within the central portion of any given scene. All of the Landsat scenes used in this study were atmospherically corrected using the ATCOR module of the ERDAS Imagine software package, and the resultant data represent the reflectance at the ground level.

3. Results and discussion

3.1 Beet yield and sugar content

The laboratory results from the beet harvested are shown in Table 1. Statistically, the beet weights (BW) and sugar contents (SC) for each zone of fields, except for the field PC26, are not significantly different from each other (p<0.05). The difference found for the field PC26 was due to extremely high soil nitrogen concentration in zone 3 (Fig. 1-b).

Table 1 Sugar beet yield and content. The numbers in bold suggest that they are significantly different from the others of the same field.

Field	Zone # (points)	Mean (Std) BW (t ac^{-1})	Mean (Std) SC (g g^{-1})
PC26	1 (5)	20.16 (2.23)	16.57 (0.41)
	2 (6)	22.51 (1.08)	16.44 (0.87)
	3 (3)	**27.00 (1.81)**	**14.35 (0.21)**
GW282	1 (5)	25.52 (1.81)	14.05 (0.82)
	2 (4)	23.48 (1.29)	14.38 (0.56)
	3 (4)	23.90 (2.37)	13.90 (0.27)
RC00	1 (3)	19.95 (2.32)	16.69 (0.04)
	2 (3)	20.58 (2.02)	17.19 (0.45)
	3 (3)	**24.87 (0.65)**	17.04 (0.13)
AT13	1 (3)	19.83 (0.65)	18.54 (0.50)
	2 (3)	19.49 (0.77)	18.22 (0.16)
	3 (3)	21.73 (2.93)	17.95 (0.11)

3.2 Hyperspectral reflectance

The correlations of the canopy reflectance at each hyperspectral wavelengths with the beet weight and the sugar contents are shown in Figure 2. Overlaid on the Fig. 2 are the multispectral bands of the Landsat TM sensor. The maximum correlations (the absolute values) can be found in the near infrared (NIR) wavelengths (750 – 900 nm) for the beet weight and in the mid infrared (MIR) (1550-1750 nm and 2150-2350 nm) for the sugar content. Clevers (1997) showed that the magnitude of canopy's reflectance in NIR is closely related to sugar beet productivity, which in turn, determines the beet weight. At the end of growing season, the sugar beet under water stress will tend to consume less sugar, which would otherwise be burned for further growth of beet itself (Werker et al. 1999; Landsdorf et al. 2000). The reflectance at MIR normally increases with the canopy wetness.

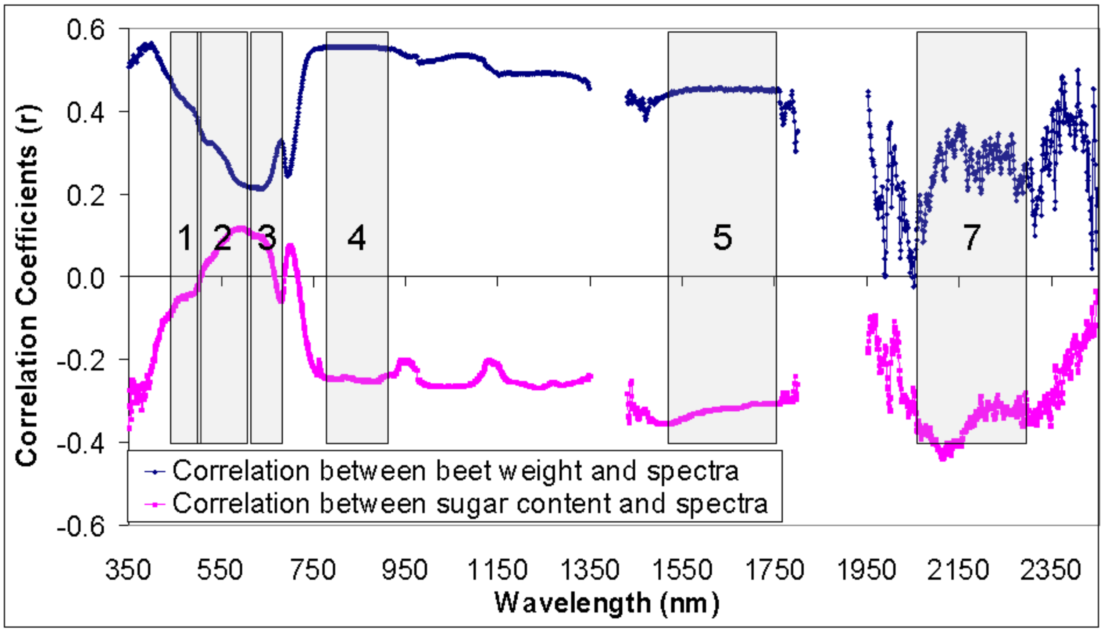

Figure 2 Correlation coefficients of the spectral reflectance of the beet canopy with the beet weight (blue curve), and with the beet sugar content (purple curve), as a function of wavelengths. The boxes in grey colors are the spectral band width of the Landsat TM sensor. N=74

We simulated the multispectral reflectance for each Landsat TM band (grey boxed of Fig. 2) using the hyperspectral ground measurements, and derived the following indices:

NDVI =	(NIR – Red) / (NIR + Red)	(1)
GNDVI =	(NIR – Green) / (NIR + Green)	(2)
EVI =	((NIR – Red) / (NIR + 6*Red – 7.5*Blue + 1))*2	(3)
NVI52 =	(MIR5 – Green) / (MIR5 – Green)	(4)
NVI7521 =	((MIR5+MIR7)-(Blue+Green)) / ((MIR5+MIR7)+(Blue+Green))	(5)

where Blue, Green, Red, NIR, MIR5 and MIR7 represent the reflectance at Landsat bands 1, 2, 3, 4, 5, and 7, respectively. The Indices 1-3, namely, the Normalized Difference Vegetation Index (NDVI), the Green Normalized Difference Vegetation Index (GNDVI) and the Enhance Vegetation Index (EVI), are typically used to map the vegetation productivity because of the use of NIR signal in the index construction (Guerif and Duke 1998; Guerif and Duke 2000; Huete et al. 2002). We also defined two more indices, the index 4 (NVI52) and the index 5 (NVI7521), both of which include the reflectance signal in the MIR and therefore are expected to be sensitive to the wetness of the beet field. Using indices calculated with multiple bands instead of reflectance at a single band is to normalize the data and reduce the systematic errors associated with the remote sensing observations. Even though the reflectances at the blue and the green are sensitive to the sugar beet leaf nitrogen (Beeri et al. 2004), they are relatively less covarying with the beet weight and sugar content. We expected that these indices would largely preserve the covariance with the beet weight and the sugar content, as found in Fig. 2.

3.3 Predict beet weight using Landsat images

We calculated the indices 1 – 3 using the Landsat images, and Table 2 summarized the correlations between these different indices and the beet weight. The performances are different for the different fields. Within each field, where normally the beet seeds and soil are of the same type, it is clear that the performance improves as the season goes from June and early July to late July and August, during which the sugar beet canopy is fully developed. EVI has better results than the other two indices. Averaging the images from different months, however, does not improve the performance significantly (merely 1-2%).

Table 2 Pearson correlation coefficients (r) between remote sensing indices and beet weight. The values in bold denote the correlations are significant (p<0.05).

Field	Image Date	NDVI	GNDVI	EVI
RC00	06/15/03	0.31	0.25	-0.46
AT13	06/13/03	0.00	-0.06	0.24
PC26	06/11/02	**0.60**	0.29	**0.62**
GW282	06/11/02	0.05	0.51	0.50
RC00	07/08/03	**0.80**	**0.79**	**0.79**
AT13				
PC26	06/27/02	**0.79**	**0.76**	**0.76**
GW282	06/27/02	0.14	0.25	0.37
RC00	07/24/03	**0.88**	**0.86**	**0.87**
AT13	07/24/03	0.31	0.38	0.38
PC26	07/29/02	0.49	**0.66**	**0.54**
GW282	07/29/02	0.23	0.32	0.46
RC00	08/18/03	**0.88**	**0.83**	**0.82**
AT13	08/16/03	0.45	0.47	0.53
PC26	08/05/02	**0.66**	**0.66**	**0.73**
GW282	09/15/02	0.39	-0.44	0.25
RC00	July-Aug mean	**0.86**	**0.84**	**0.83**
AT13	July-Aug mean	0.39	0.44	0.45
PC26	July-Aug mean	**0.63**	**0.68**	**0.67**
GW282	July-Aug mean	0.36	0.20	0.42
RC00	June-Aug mean	**0.86**	**0.85**	**0.82**
AT13	June-Aug mean	0.37	0.46	0.47
PC26	June-Aug mean	**0.74**	**0.68**	**0.75**
GW282	June-Aug mean	0.07	0.10	0.40

3.4 Predict sugar content using Landsat images.

The same analysis was conducted for the sugar content, and the results are summarized in Table 3. We also included single band 5 in the analysis. Before the full cover of the canopy (in June and early July), these indices have positive correlation and after the fully development of the canopy, the correlations become negative. After sugar beets are fully developed, sugar beets will grow at the expenses of sugar content. During this period, a water shortage would limit the further grow of sugar beets and therefore preserve the sugar content(Vandendriessche 2000b). The use of averaged values of the July-August images, in most of the cases, improves the performance. The use of single band, Band 5, without the normalization, yields very inconsistent results. This is probably due to the errors introduced during the atmospheric correction.

Table 3 Pearson correlation coefficients (r) between remote sensing indices and sugar content. The values in bold denote the correlations are significant ($p<0.05$).

Field	Image Date	Band 5	NVI52	NVI57/21
RC00	06/15/03	-0.21	0.30	0.19
AT13	06/13/03	0.01	0.51	0.64
PC26	06/11/02	0.25	0.35	0.30
GW282	06/11/02	-0.29	0.36	0.41
RC00	07/08/03	-0.49	-0.47	-0.41
AT13				
PC26	06/27/02	0.44	**0.75**	**0.76**
GW282	06/27/02	0.02	0.02	0.02
RC00	07/24/03	0.55	0.20	-0.49
AT13	07/24/03	-0.40	0.20	0.21
PC26	07/29/02	-0.08	**-0.57**	**-0.50**
GW282	07/29/02	**-0.59**	-0.45	-0.13
RC00	08/18/03	0.24	-0.04	-0.26
AT13	08/16/03	-0.45	-0.57	**-0.73**
PC26	08/05/02	-0.14	**-0.65**	-0.47
GW282	09/15/02	**-0.66**	-0.45	**-0.57**
RC00	July-Aug mean	-0.47	**-0.68**	-0.61
AT13	July-Aug mean	-0.46	-0.43	-0.13
PC26	July-Aug mean	-0.11	**-0.64**	-0.51
GW282	July-Aug mean	-0.54	-0.55	-0.50
RC00	June-Aug mean	-0.41	-0.31	-0.61
AT13	June-Aug mean	-0.12	0.11	0.06
PC26	June-Aug mean	0.31	0.47	**0.60**
GW282	June-Aug mean	-0.37	-0.39	-0.30

4. Summaries.

To summarize, these results show the potential of Landsat images to be used for prediction of beet weight and sugar content. For some fields, the remote sensing indices are well correlated with the beet weight and sugar content. However, the performance varies significantly across the fields, and it is still challenging to derive a universal prediction model for sugar beets that can be applied to such a large scale as the Red River Valley. To improve the predictability, we need to integrate information from other data sources such as soil type, rainfall, air temperature, leaf evaporation and solar radiation (Werker and Jaggard 1998; Werker et al. 1999; Vandendriessche 2000a) during the growing season.

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