Leaf area index from CHRIS satellite data and applications in plant yield estimation[1]

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ABSTRACT

In situ weather sensors provide temporally dense but spatially sparse information. Conversely, remote sensing data tend to provide spatially dense but temporally sparse information. The fusion of weather, soil, and remote sensing data in state-of-the-art plant growth models provides a powerful tool for estimating plant biomass and yield, and for monitoring the impacts of drought or management practices on a local or regional level. In 2003, a two-year project funded in part by Precarn Incorporated and by its participants, MDA, Natural Resources Canada (NRCan), Agriculture and Agri-food Canada (AAFC), York University, and Radarsat International (RSI) commenced to develop an intelligent sensorweb system for yield prediction in agricultural crops and rangeland. Two sites were selected in Alberta, a wheat field and rangeland. In situ instrumentation was installed in the spring of 2004 to record soil moisture to a variety of depths, soil temperature, air temperature, rainfall, incoming solar radiation, and wind speed and direction, among other variables. Throughout the season, data from the Compact High Resolution Imaging Spectrometer (CHRIS) were acquired to derive leaf area index information. Ground data, including biomass and leaf area index, were collected monthly at the rangeland site and weekly or tri-weekly at the crop site. A good relationship was observed between ground-based and remote sensing derived leaf area index in the case of wheat ($r^2 > 0.7$). The correlation was poorer in the case of rangeland, probably due to the low productivity of the system and the presence of litter. Preliminary conclusions are that in wheat, remote sensing data may be useful for extrapolating plant models in space, whereas in rangeland the impact of litter needs to be evaluated.

Keywords: Remote sensing, vegetation index wheat, rangeland, plant growth models.

1. INTRODUCTION

In the past 30 years, a considerable amount of research has focused on prediction of crop yield using remote sensing imagery. Despite this intensive effort, for a number of reasons, remote sensing alone is not effective in predicting plant yield [1,2]. Both operational and environmental limitations often preclude the acquisition of optical remote sensing data at critical stages in the crop growth cycle. In addition, remote sensing data may not provide all the necessary information to estimate yield, for example local weather or soil moisture at different depths in the rooting zone. Typically, climatic information is obtained from in situ weather sensors. Although weather sensors provide adequate temporal information, their spatial coverage is limited.

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The fusion of temporally sparse but spatially dense remote sensing, and spatially sparse and temporally dense in-situ weather data with plant growth models offers a potentially powerful tool for predicting the impacts of management practices or environmental parameters on production of both annual cropping and rangeland systems. In cropping systems, the effects of drought or pest infestation could be estimated and remedial action taken to mitigate crop loss. The information would also be valuable each year in the planning of export markets and local processing plant logistics while at the field scale it could be used in determining within field variability and aid in the implementation of differential management practices [3]. In a rangeland scenario, knowledge of the impact of drought or management strategies on forage yield would be useful in determining stocking rates or in monitoring the health of these ecosystems which provide habitat for a number of wildlife species.

In 2003, building on earlier work involving intelligent sensorweb [4,5,6], a two-year project funded in part by Precarn Incorporated and by its participants, MDA, Natural Resources Canada (NRCan), Agriculture and Agri-food Canada (AAFC), York University, and Radarsat International (RSI) commenced to develop an in situ intelligent sensorweb system (ISIES) that integrates real-time in situ measurements with remote sensing and vegetation growth modeling for yield prediction in agricultural crops and rangeland. There are many aspects to this project as indicated in the overview provided in Teillet et al.[7].

This paper focuses on the optical remote sensing aspects of the ISIES project. The integration of remote sensing information into crop modeling is not new [8,9]. Green leaf area index (LAI), canopy biomass, absorbed photosynthetically active radiation (APAR), and total N level estimates from remote sensing have been used in crop modeling studies [10,11,12]. However, LAI is the most influential parameter in terms of the capacity of a crop to grow, as absorbed radiation results in all assimilation. The change in LAI over time is indicative of the stage of crop growth [10,11]. LAI estimates can be used in a variety of ways with plant growth modeling. For example, periodic estimates of LAI could be used to drive crop models, to update, re-initialize or re-calibrate crop models and yield predictions [8]. In the context of the ISIES system, climatic events that impact crop growth, as observed from the crop modelling, could trigger a satellite system to acquire images over selected areas and enable extrapolation of yield prediction to a much larger area.

A number of empirical relationships have been developed between LAI and vegetation indices [13]. The majority of these indices are based upon the same wavelengths as the normalized difference vegetation index and constitute a "family" of indices. Inherent in these indices are the confounding factors of plant health or "greenness" and amount of plant material as well as the problem of signal saturation at higher LAI values. Recently, a novel algorithm for estimating LAI that decouples plant "greenness" from the amount of plant material was proposed [14]. The algorithm was developed at an Ontario site using select crops and a Compact Airborne Spectrographic Imager (CASI) airborne dataset. The objective in the component of the ISIES work reported here is to evaluate the use of these algorithms with data from the Compact High Resolution Imaging Spectrometer (CHRIS) system aboard the PROBA satellite to estimate LAI of wheat and also rangeland vegetation. The success of integrating remote sensing information into crop models will depend upon the accurate estimate of LAI.

2. METHODS

Two test sites were selected in southern Alberta to represent annual cropping and rangeland (Figure 1).

2.1. Annual Crop Test Site

The annual crop site located near Lethbridge, Alberta (Lat. 49°43′N, Long. 112°8′W) represents a dryland zero-till management system. The crop rotation is typically a cereal-broadleaf. Annual average precipitation (1971-2000) is 380 mm with 270 mm falling from April-August; average minimum and maximum temperature ranges from -13.1 °C and -1.8°C in January and 10.8°C and 25.8°C in July, respectively. The soil of the area is a Dark Brown Chernozemic (Typic Haploborall) clay loam belonging to the Lethbridge series. The parent material is lacustrine. The landscape is flat. The test field of approximately 250 hectares (~600 acres) was planted to spring wheat (cv Superb) on April 17, 2004.

During the course of the growing season crop growth stage, LAI and above ground biomass data were acquired to characterise growth (Table 1). The ground derived LAI data were used as verification for the remote sensing derived LAI products and for the plant growth model predictions. Sixteen sample sites were distributed throughout the field where measurements were made (Figure 2). The sample sites were marked with survey flags, and positions were recorded using a CDGPS connected to a Trimble GeoXM handheld unit. The dates of sampling are shown in Table 1.

Weekly leaf area index measurements were taken. The plants on May 16 were small and destructive LAI sampling was done. The leaf area of the plants harvested for the biomass estimates was measured using an LI-3100 Leaf Area Meter (LiCor, Lincoln, Nebraska). The values were converted to LAI using the following formula:

$$LAI = \text{leaf area (cm}^2\text{)/sample area (cm}^2\text{)}. \quad (1)$$

Thereafter, all other LAI measurements were made using an LAI-2000 Plant Canopy Analyzer (Li-Cor, Lincoln, Nebraska). The LAI-2000 was configured for analyzing row crops, one reading was taken above the canopy, followed by four readings below the canopy in a diagonal transect between two rows. This was done twice and the readings combined to give a one reading per sample site.

Table 1. Growth staging, LAI and biomass data collection schedule for the 2004 season at the spring wheat site.

Measurement dates		
Growth staging	**Leaf area index**	**Biomass**
May-17-04	May-17-04	May-10-04
May-31-04	May-31-04	May-17-04
Jun-08-04	Jun-08-04	Jun-03-04
Jun-14-04	Jun-14-04	Jun-22-04
Jun-23-04	Jun-23-04	Jul-13-04
Jun-29-04	Jun-29-04	Aug-03-04
Jul-08-04	Jul-8-04	Aug-16-04
Jul-13-04	Jul-13-04	
Jul-23-04	Jul-23-04	
Jul-28-04	Jul-28-04	
Aug-04-04	Aug-04-04	
Aug-10-04	Aug-10-04	
Aug-17-04	Aug-17-04	

2.2. Rangeland Test Site

The Antelope Creek Ranch (Lat. 50°37′N, Long. 112°10′W, Elevation ~750 m) approximately 15 km west of Brooks, Alberta was selected as the rangeland test site. Antelope Creek Ranch, established in 1986, is a multi-disciplinary, multi-agency research site. The primary objectives of the ranch are to manage the ecosystem in such a way that productive plant cover is available to livestock and wild life, and that there is adequate nest cover for waterfowl. The ranch serves as a demonstration to producers and resource managers in the mixed grass region that range improvement through specialized grazing systems benefits both livestock and wildlife.

The vegetation represents the *Stipa-Bouteloua-Agropyron* community of the mixed grass prairie ecoregion. Annual precipitation averages 340 mm with 240 mm falling from April-August; average temperature ranges from -12.5° C in January to 18.4°C in July. The soils of the area are Brown Solodized Solonetz (Acridic Natriboroll) and Solonetzic Brown clay loam to loam. The parent material is mainly till. Approximately 30% of the area has eroded pits or areas of patchy micro-relief due to differential soil erosion. The B-horizon is exposed in some eroded pits, and plant growth is usually very sparse. The ranch consists of 2225 ha of managed grasslands including four native grassland fields, a crested wheatgrass field, a pivot field and a flood field. The ISIES project focuses on the native grassland fields, which are in a deferred, rotational grazing pattern (i.e., the field grazed first changes every year). Each field is approximately 450 ha in size. In 2004, field 2 was grazed first (July 17 to August 3), followed by fields 3 (August 4 to August 22), 4 (August 23 to September 10) and 1 (September 25 to October 12).

At Antelope Creek Ranch, plant samples were collected monthly throughout the growing season in three fields (Table 2). In each field, ten sample points were established (Figure 3). The sample points were marked with a labelled survey flag, and the positions were recorded using a CDGPS connected to a Trimble GeoXM handheld unit. At ten sites, a total of 15 samples were collected per field on each harvest date; duplicate samples were taken at five sites due to landscape variability. For each sample, a 0.5 m × 0.5 m quadrat was randomly selected within a 2 m radius of the CDGPS sample point location. From the main 0.5 m × 0.5 m quadrat, a sub-quadrat of 0.2 m × 0.2 m was collected for separation into green (current year growth) and litter (past growth) material. All biomass was harvested using hand shears at ground level. The 0.2 m × 0.2 m sub-samples were sorted by hand into new, green growth and old, brown litter. All mosses and lichens were discarded. The 'green' and 'litter' sub-samples were each weighed and the leaf area in each fraction determined by running the plant tissue through a LI-3100 Leaf Area Meter (LiCor, Lincoln, Nebraska). The LAI was calculated for the green as opposed to litter vegetation using the following equation:

$$\text{LAI} = \text{green leaf or litter area } (\text{cm}^2)/\text{sample area } (\text{cm}^2). \qquad (2)$$

The remainder of the plant matter from the 0.5 m × 0.5 m quadrat was weighed and the amount of green and litter estimated using the fractions derived from the sub-sample.

Table 2. Manual LAI and biomass data collection schedule for the 2004 season at the Antelope Creek test site.

Measurement	Collection Date
LAI & Biomass	May-25-04
LAI & Biomass	June-16-04
LAI & Biomass	July-14-04
LAI & Biomass	August-18-04
LAI & Biomass	Sep-15-04 & Sep-16-04
LAI & Biomass	Oct-26-04

2.3. Remote Sensing Data

A total of 14 Compact High Resolution Imaging Spectrometer (CHRIS) images were acquired at the crop and rangeland sites in 2004 (Tables 3 and 4). The images were of 36 m spatial resolution, 14 × 14 km area and 62 spectral bands. The optical data were atmospherically corrected using the CAM5S radiative transfer code [15] to yield spectral reflectance images. The aerosol optical depths used in the corrections were estimated using climatological averages provided by the Networked On-line Mapping of Atmospheric Data (NOMAD) database maintained by the University of Sherbrooke [16]. LAI images were created using the methodology of Haboudane et al. [14]. The method involves the Modified Triangular Vegetation Index (MTVI2):

$$MTVI2 = \frac{1.5*(1.2*(R_{800}-R_{550})-2.5*(R_{670}-R_{550}))}{\sqrt{(2*R_{800}+1)^2-(6*R_{800}-5*\sqrt{R_{670}})-0.5}}, \qquad (3)$$

$$LAI\ MTVI2 = 0.2227*\exp(3.6566*MTVI2). \qquad (4)$$

The derived LAI images were georeferenced to WGS-84, Universal Transverse Mercator (UTM) 12N, pixel size 36 × 36 m, using a minimum of 20 GCPs. The georeferencing threshold was set at RMS < 0.20 and the images were warped using 1st order polynomial, nearest neighbour resampling. The respective sampling points were overlain on the LAI derived images and the values extracted for a three by three window of pixels at each sample point.

Table 3. 2004 CHRIS Acquisitions for the Lanier Test Site.

Date	Status	Comments
May-01-04	Acquired	
May-17-04	Acquired	Clouds
Jun-03-04	Acquired	
Jun-20-04	Failed	
Jun-27-04	Acquired	Clouds
Jun-28-04	Acquired	
Jul-14-04	Acquired	
Jul-21-04	Acquired	
Jul-30-04	Failed	
Aug-07-04	Failed	Priorities
Aug-15-04	Failed	Priorities
Sep-08-04	Acquired	But no more crop!!

Table 4. 2004 CHRIS Acquisitions for the Antelope Creek Test Site

Date	Status	Comments
Apr-22-04	Failed	
May-16-04	Acquired	
May-25-04	Acquired	
Jun-18-04	Acquired	Clouds
Jun-19-04	Acquired	
Jul-22-04	Failed	
Jul-29-04	Acquired	
Aug-07-04	Failed	
Sep-01-04	Acquired	
Oct-04-04	Acquired	

2.4. Statistical Analysis

The relationship between the remote sensing and ground based LAI was examined using simple graphing and correlation analyses.

3.0 RESULTS

3.1. Annual Crop Test Site

The visual changes in the wheat crop over the 2004 growing season are shown in the photographs in Figure 4; the seasonal trajectory for LAI as measured using destructive and LAI-2000 sampling is shown in Figure 5. The crop was seeded on April 17 and harvested the week of September 1 – 8. As anticipated peak LAI occurred early in July (DOY = 190) at the start of flowering. Thereafter, LAI declined steadily until harvest. Of the eight CHRIS images obtained over the crop site only six could be used, as they were cloud free. The LAI maps derived from the CHRIS imagery showed a progression similar to the ground-based data, as LAI increased to mid-July and then decreased (Figure 6). Although a reasonable relationship was found between the ground based and image derived LAI values ($r^2 = 0.70$), there was no data acquisition between June 3 (DOY = 155) to June 28 (DOY = 180) when the crop is most actively growing and LAI increase form <1 to ≥3 (Figure 7). There was a tendency for the measured LAI to exceed the CHRIS derived LAI values, particularly on July 28 (DOY = 203). The LAI-2000 measures total LAI and does not discriminate green from senescent vegetation. The LAI derived from the CHRIS imagery differentiates green LAI from senescent LAI, which likely accounts for this discrepancy. In the coming field season, when the wheat starts to senesce, destructive samples will be taken to measure green LAI as opposed to total LAI.

Initial results are encouraging with respect to the relationship between the ground-based and modeled output for the LAI measurements (Figure 8). The LAI predicted from the MAAS-based crop model throughout the growing season showed a similar trend to the ground-based LAI, with peak growth (LAI ~4) in both instances being in mid-July. It is anticipated that given the relationship between the ground-based and CHRIS data, that LAI maps derived from the remote sensing imagery would also match well with the modeled data.

3.2. Rangeland Site

The rangeland site is of low productivity as shown in the ground-based photographs (Figure 9), the ground-based LAI measurements and the CHRIS derived LAI maps (Figure 10). The variable nature of the rangeland landscape is reflected in the ground-based LAI measurements where the standard deviations were high (Figure 11). In the short-grass prairie green up usually starts in May; however, in 2004 due to logistical problems ground-based sampling commenced in June. The ground-based and CHRIS LAI values remained fairly constant from June through September. In October, the ground based LAI tended to decrease but the CHRIS LAI did not. There was a good relationship between the CHRIS derived and ground-based LAI mid-season, but at the beginning and end of the season the LAI estimates from the CHIRS data exceeded those of the ground-based measurements (Figure 11). The actively growing green plant matter early and late in the season is often masked by the plant litter (senescent vegetation from past and current growing seasons), which may impact the derivation of LAI from remote sensing imagery and lead to the differences observed.

4. CONCLUSIONS

This is the first year of a two-year study. The results to date suggest that wheat LAI can be successfully estimated using CHRIS satellite imagery and that the LAI could potentially be fused with in situ weather data and crop modeling to spatially extrapolate crop growth. In rangeland, which is of very low productivity, the estimation of productivity in terms of LAI was adequate mid-season, which is the time of highest productivity, but the presence of plant litter is a complicating factor.

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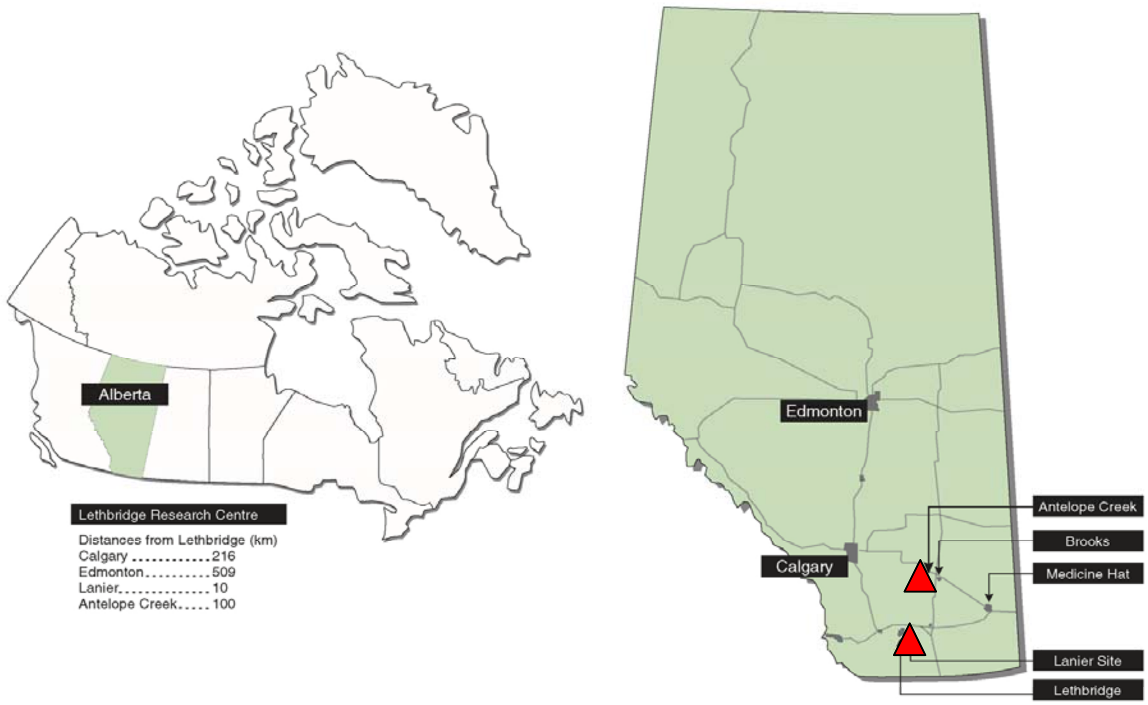

Figure 1. Location of test sites in Alberta.

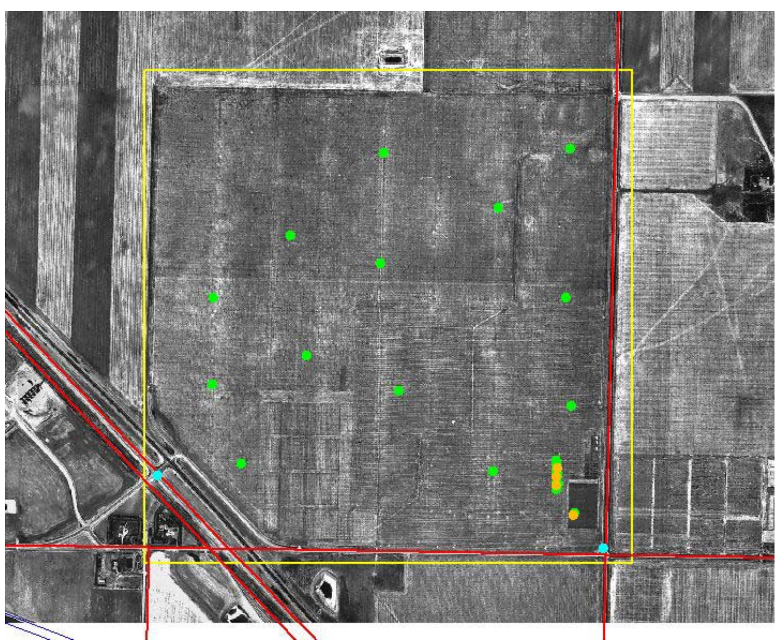

Figure 2. Location in situ sensors (yellow points), plant sampling sites (green points) and field access (blue) for the annual cropping site.

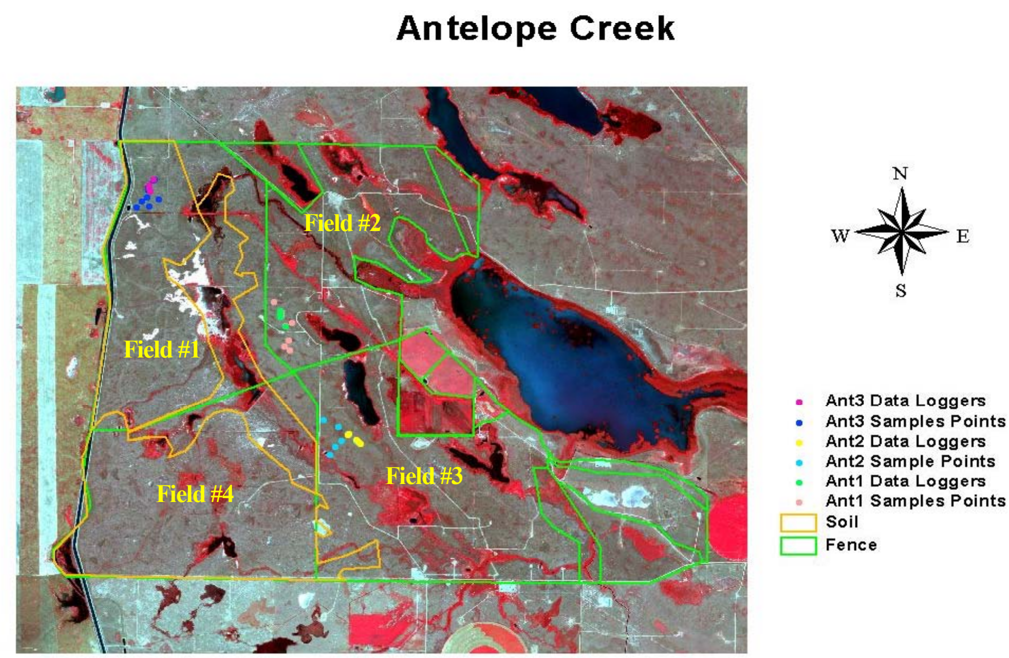

Figure 3. Location of LAI and biomass sampling sites for the Antelope Creek test site.

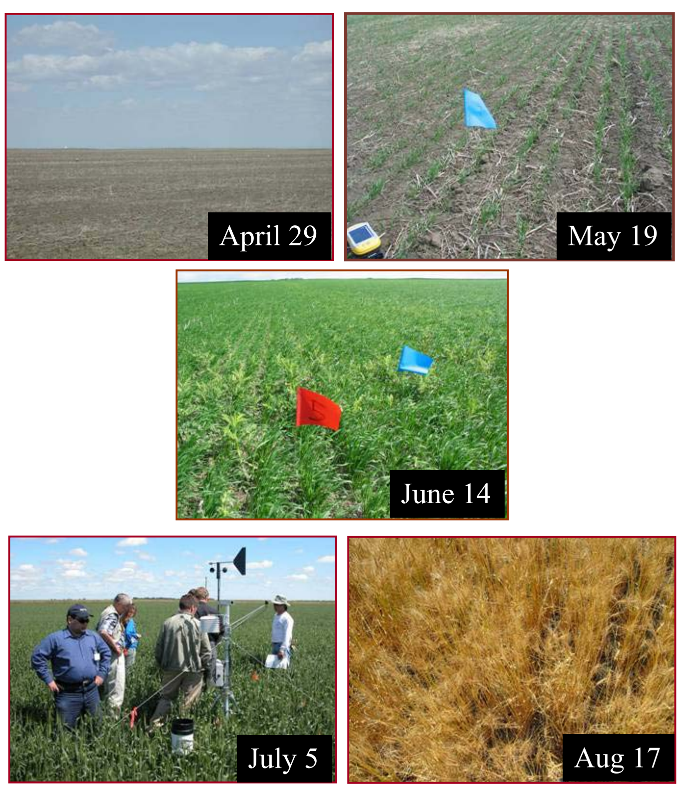

Figure 4. Wheat crop at various time intervals throughout the 2004 growing season.

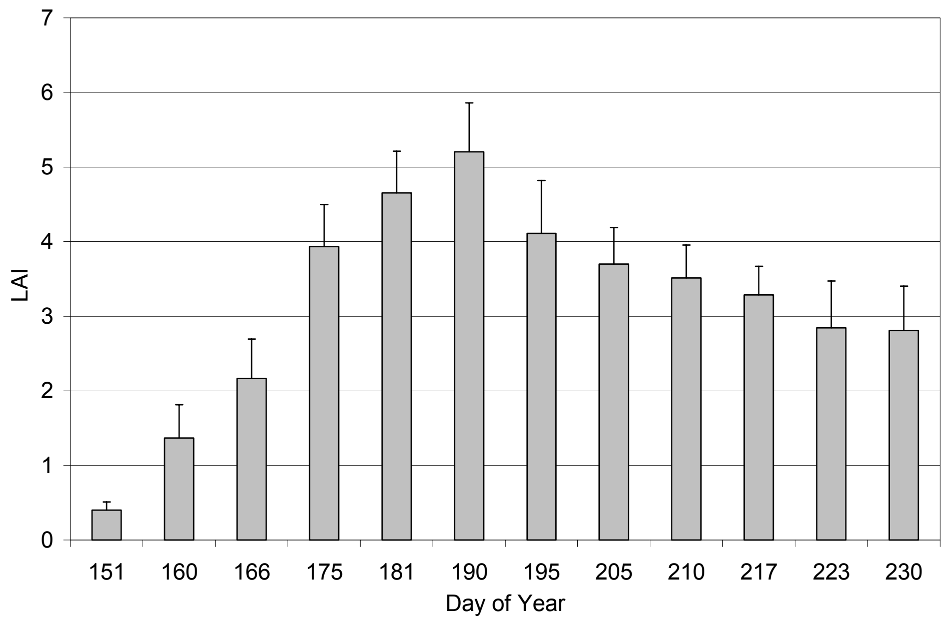

Figure 5. The seasonal trajectory of the wheat LAI as measured with the LAI-2000.

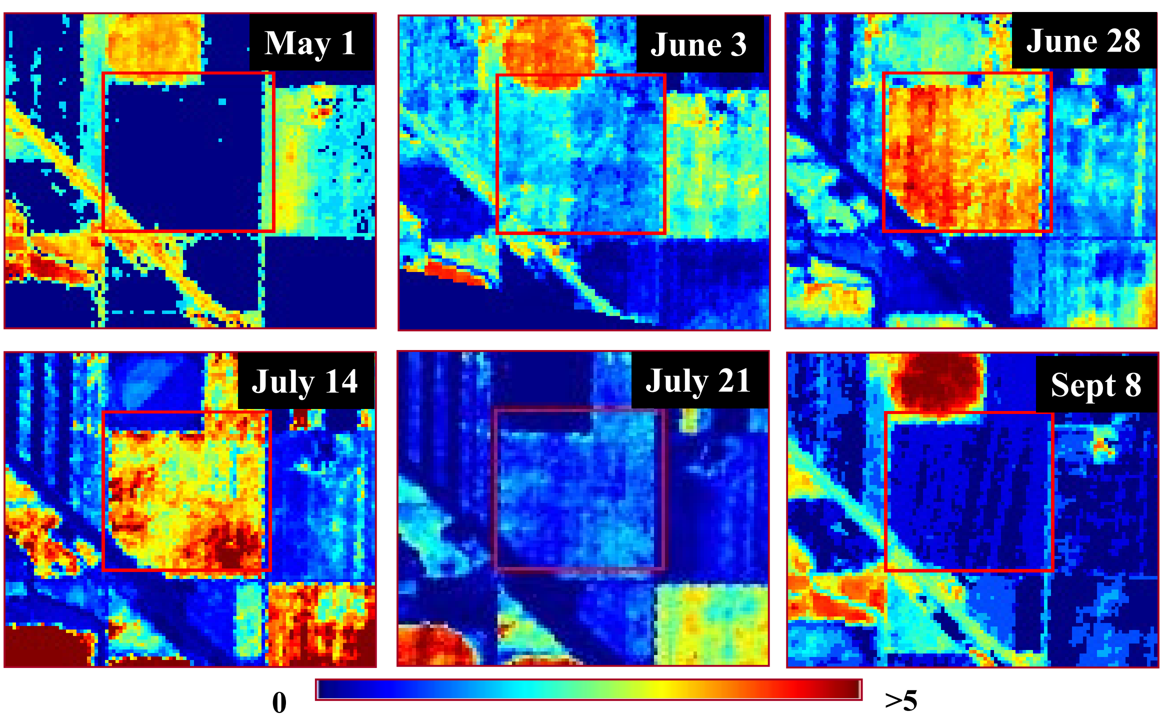

Figure 6. The seasonal LAI maps derived from the CHRIS imagery for the annual cropping site.

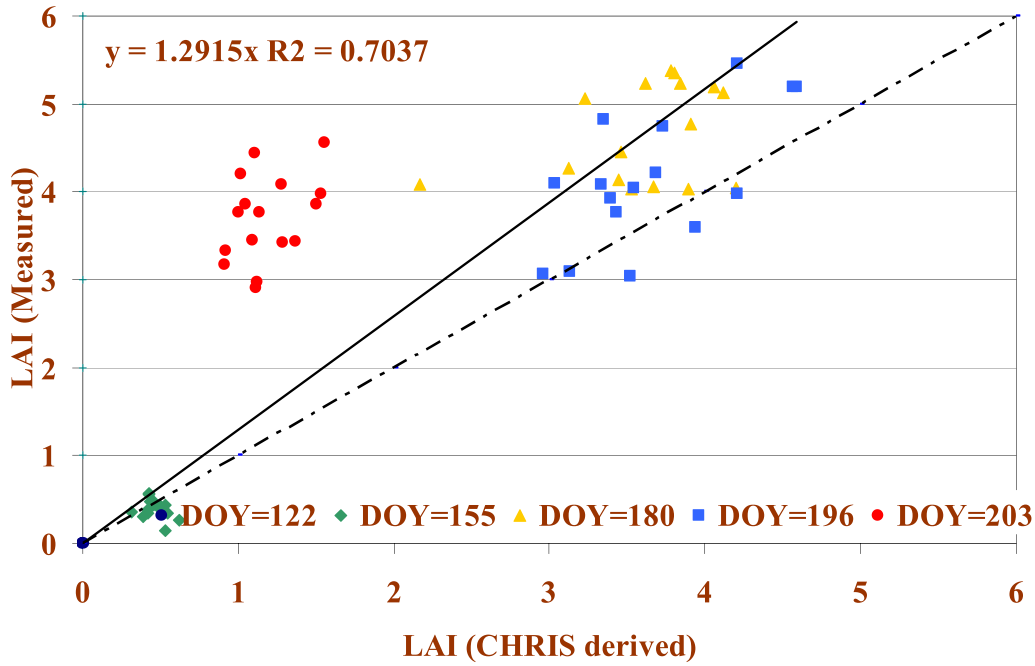

Figure 7. The relationship between LAI as measured with the LAI-2000 and derived from the CHRIS imagery at the annual cropping site.

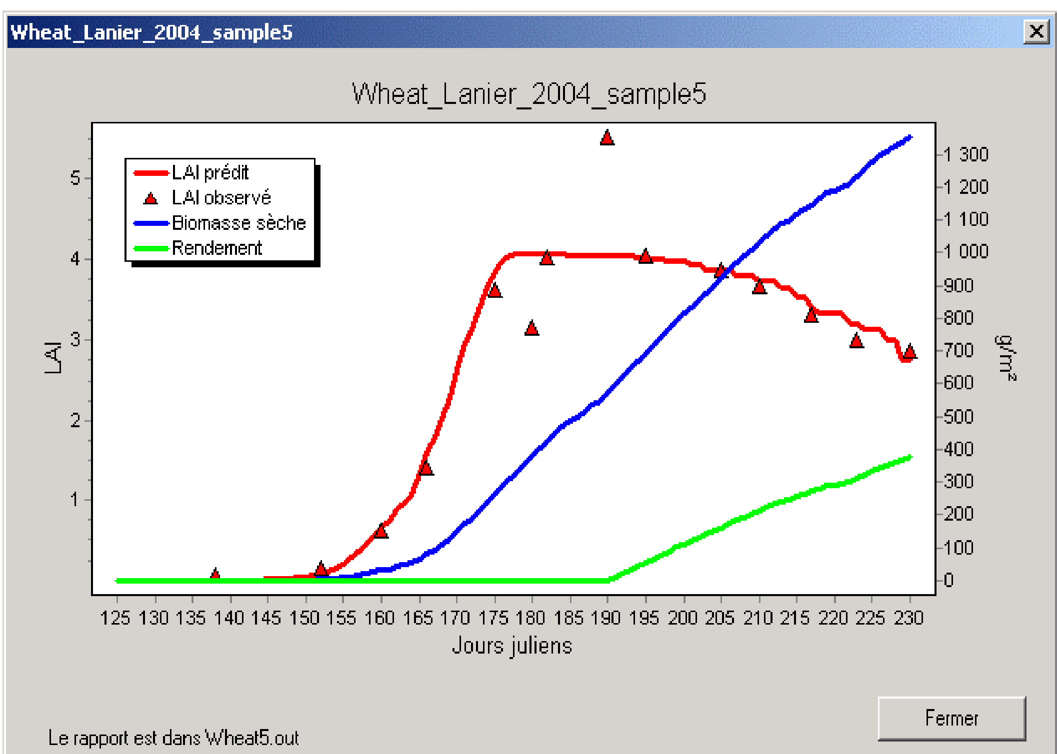

Figure 8. The relationship between wheat LAI predicted using the MAAS model and ground-based LAI measured using an LAI-2000.

Figure 9. Antelope Creek rangeland test site.

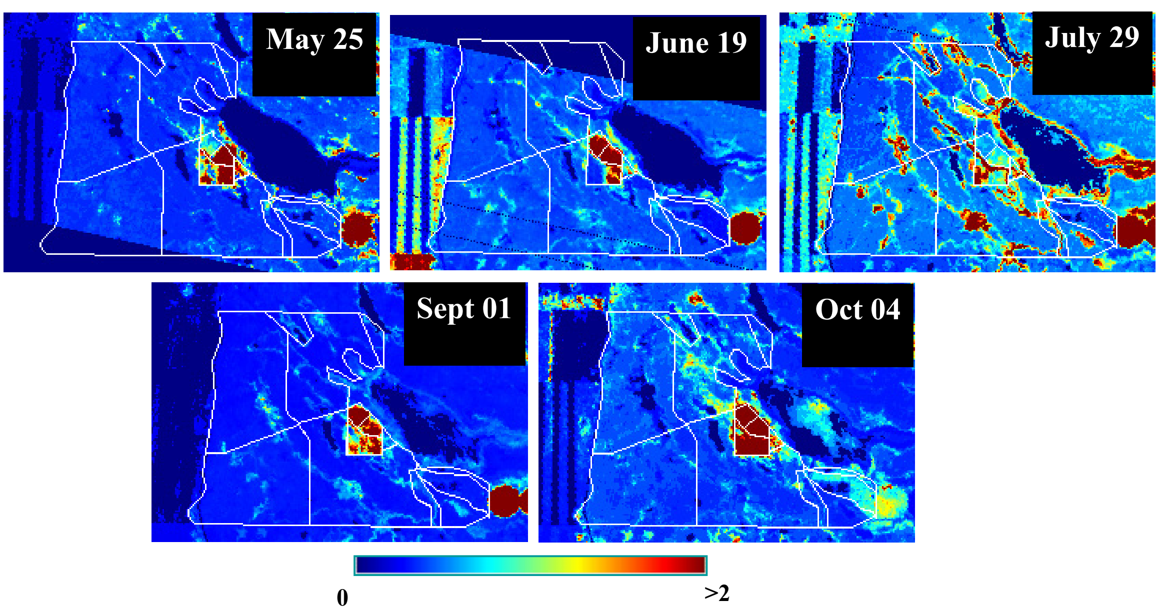

Figure 10. The seasonal LAI maps derived from the CHRIS imagery for the rangeland site.

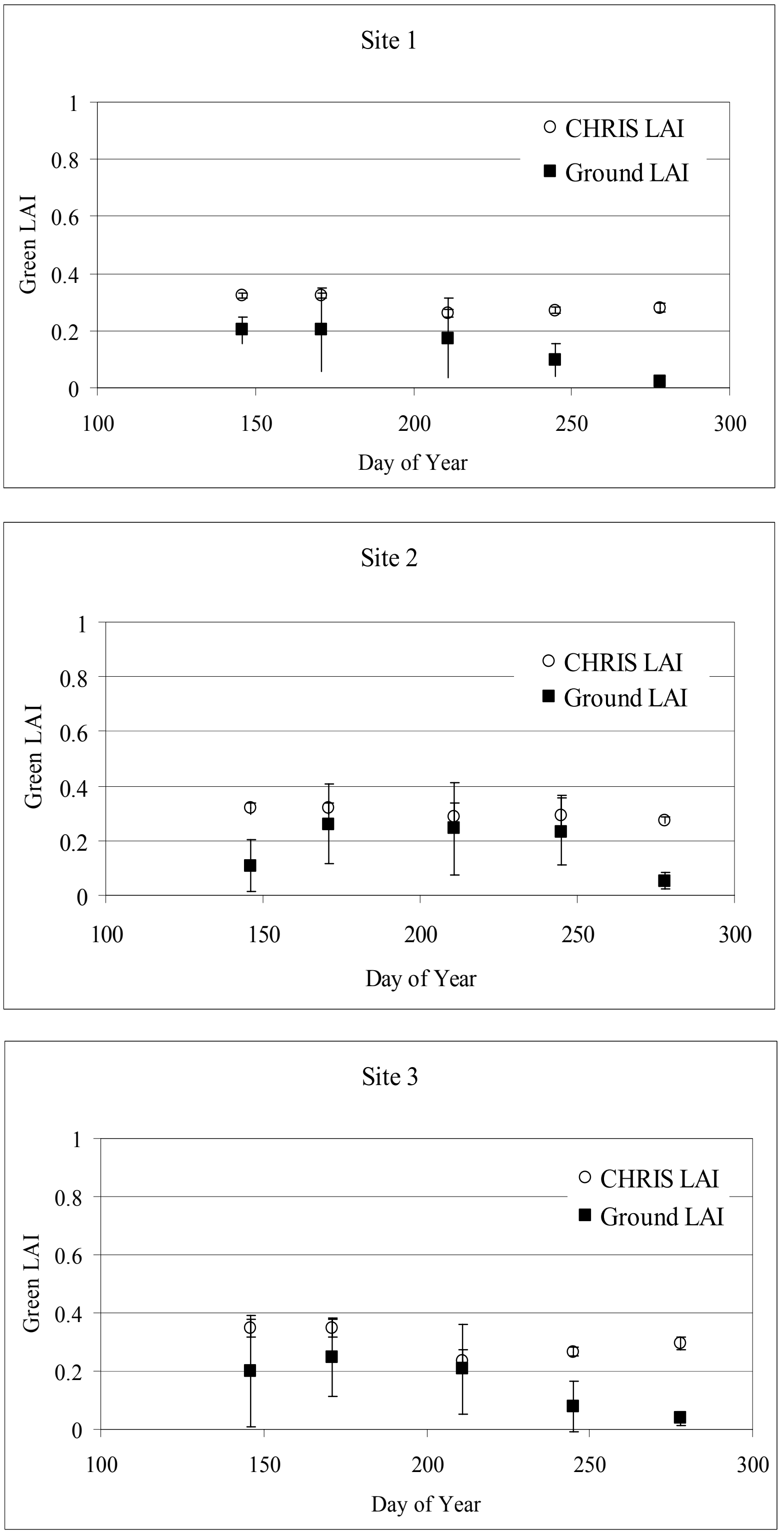

Figure 11. The relationship between LAI derived from CHRIS data and that measured on the ground through destructive sampling at Antelope Creek.