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An integrated Earth sensing sensorweb for improved crop and rangeland yield predictions

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Abstract. This paper outlines research and development towards an integrated Earth sensing sensorweb system for improved crop and rangeland yield predictions. After introducing the concepts of integrated Earth sensing and *in-situ* sensorwebs, the paper describes the key aspects and innovations of an Intelligent Sensorweb for Integrated Earth Sensing (ISIES). ISIES incorporates a sensorweb that provides automatic and continuous *in-situ* measurements, as well as advanced crop growth models and leading-edge sensorweb-enabled OpenGIS compliant web services. A key component of each *in-situ* sensorweb node is SmartCore, a compact device developed to control sensor data traffic autonomously and to communicate wirelessly in two-way mode with the ISIES central server. The system server integrates the *in-situ* sensorweb data with remote sensing data and crop models automatically to provide maps of leaf area index, soil moisture and biomass, as well as improved predictions of crop and rangeland yield.

Introduction

The economic well being of significant regions of Canada, as well as other countries, is determined by rangeland forage abundance and agricultural crop yield. Early indicators of vegetation health problems can be highly beneficial because management decisions can be made to mitigate the economic and social impact of disasters. More generally, the ability to accurately predict and assess rangeland productivity and crop yield has important commercial, environmental and community benefits.

An established approach to help solve this prediction and assessment problem has been the use of satellite remote sensing data, supported by periodic manual ground reference data collection, to drive relatively simple vegetation models. However, it is widely acknowledged that this approach is not sufficient. The space-based and surface data have not been integrated in a fully self-consistent way. A key missing ingredient is the ability to obtain continuous measurements to ensure that time-critical meteorological and vegetation growth events are not missed and that important patterns in the time series are recognized and used in the predictive models.

The advanced technologies of today make it possible to pursue more integrated approaches to Earth sensing that encompass both remote and *in-situ* sensing. This paper provides an overview of the integrated Earth sensing concept and describes some initial steps towards building an integrated Earth sensing capability. It highlights research and development on an Intelligent Sensorweb for Integrated Earth Sensing (ISIES), an on-line system that integrates an *in-situ* sensorweb, remote sensing imagery and Geographic Information System (GIS) data and more advanced crop growth models, with the potential to provide improved estimates and predictions of biomass and crop yield through open and standard interfaces. Three main components were involved:

1. A smart sensorweb that provides automatic and continuous *in-situ* measurements;
2. Vegetation modelling agents that integrate all available relevant information;
3. A standard, openGIS-compliant, Internet-based infrastructure that facilitates communication between sensorweb nodes and servers and makes the data and services accessible to users.

The emphasis in this paper is on the innovations brought about in the ISIES research and development project. Detailed descriptions of the vegetation measurement campaigns and modeling efforts are beyond the scope of this overview paper and are not reported here. They will be included in other publications being prepared on different aspects of ISIES.

A list of acronyms is provided at the end of the paper.

Integrated Earth sensing and sensorwebs

At the 2002 World Summit on Sustainable Development, the point was made that "… space-derived information generally needs to be combined with *in-situ* measurements and models to obtain a holistic picture of the Earth's environment. … There is no Sustainable Development without adequate information about the state of the Earth and its environment" (Josef Aschbacher, European Space Agency (ESA)). At the World Space Congress 2002, a Panel convened to explore "An Integrated Approach to Monitoring Planet Earth" noted that ground-based (*in-situ*) monitoring systems are inadequate by several orders of magnitude. The majority of space agencies represented on the Panel stated that an integrated approach to monitoring the Earth demands that the *in-situ* sensing be a funded part of the solution offered by space agencies. This is in keeping with the integrated approach proposed for the Global Earth Observation System of Systems (GEOSS) (http://www.cgeo-gcot.gc.ca/). Indeed, the confluence of advanced technologies for Earth-based sensorwebs (Roush, 2003), Earth science satellite webs (NASA, 2000; Zhou et al., 2003), and the power of the Internet will soon provide a kind of global virtual presence (Delin and Jackson, 2001) or, in the context of Earth and environment, integrated Earth sensing (Teillet et al., 2001, 2002, 2003a).

Sensorwebs are an emerging technology that does not yet have a widely accepted definition. It is important to distinguish between sensor networks, which have been around for a while (including those enabled by the World Wide Web), and sensorwebs. Unlike other distributed sensor networks, sensorweb sensor nodes share information with each other and modify their behaviour based on collected data. In the *in-situ* context, a sensorweb is an amorphous network of spatially distributed sensor nodes that wirelessly communicate with each other both synchronously and router-free. This makes it distinct from the more typical TCP/IP-like network schemes and allows every node to know what is going on at every other node throughout the sensorweb, which thus becomes "a macro-instrument for coordinated sensing" (Delin, 2002). In the satellite context, a network of collaborating satellite platforms and sensors can be referred to as a satellite web or a sensorweb. The essential features in the satellite case are reconfigurable and interoperable satellite platforms and sensors that can decide amongst themselves when and how to acquire and downlink pertinent Earth imagery (Zhou et al., 2003). With the capability of providing an ongoing virtual presence in remote locations, many sensorweb uses are being pursued in the context of Earth and environmental monitoring, as well as for pedagogical and public access reasons. Sensorwebs could have as much impact on the uses of sensor technology as the Internet did on the uses of computer technology.

The ISIES project

Building on earlier *in-situ* sensorweb prototype demonstrations (Teillet et al., 2003b, c), ISIES was initiated in 2003 with the objective to design and develop a prototype intelligent sensorweb system that:

- Incorporates field trials of a new autonomous and wireless sensor data controller (SmartCore, described in the next Section)
- Implements new sensorweb-enabled OpenGIS compliant web services
- Implements more advanced crop growth models

- Generates sample products of soil moisture maps retrieved from remotely sensed Synthetic Aperture Radar (SAR) image data and leaf area index (LAI) maps retrieved from remotely sensed hyperspectral image data

- Integrates *in-situ* sensorweb data with remote sensing and auxiliary data, together with the crop growth models, to provide improved predictions of crop and rangeland yield

A smart sensorweb prototype was built to autonomously acquire meteorological and soil moisture data and transmit them wirelessly to a central server in Vancouver, B.C., Canada. A server was designed and developed to enable users to accurately and automatically predict biomass and crop yield using advanced vegetation models that integrate *in-situ*, remote sensing and GIS data. The server incorporates OpenGIS compliant web services to provide data and products through open and standard formats. Sensorwebs were deployed at two test sites in southern Alberta: a crop field (1.6 km by 1.6 km in area) near Lethbridge and a native rangeland site at the Antelope Creek Ranch (4 km by 4 km in area) near Brooks. Remote sensing data types used for soil moisture and leaf area index (LAI) estimates include imagery from the Radarsat-1 SAR, the Envisat Advanced SAR (ASAR), and the Compact High-Resolution Imaging Spectrometer on the Project for On-Board Autonomy small satellite (CHRIS-PROBA).

Sensorweb

The key component of each sensorweb is a SmartCore device designed and built by the Canada Centre for Remote Sensing. The SmartCore is a compact device that controls sensor data traffic autonomously and communicates with a central server wirelessly in two-way mode. Its main characteristics are: modules for data processing and radio frequency (RF) or satellite communication; digital input-output (I/O), analog I/O, RS232, I2C, and SPI interfaces; and flexibility in terms of power requirements, sensor interfacing and programmability. The main functionalities of the current SmartCore prototype are listed in Table 1.

Each SmartCore can send sensor data autonomously and wirelessly to the central server in Vancouver and can also be prompted by the central server to send data. The ISIES configuration used digital cellular modems but the configuration can be changed easily to use satellite modems. The SmartCore devices can be programmed locally or remotely to carry out aggregate calculations in the field and also to send special event alerts to the central server. It is in these respects that ISIES constitutes a smart sensorweb that can act as a macro-instrument capable of making decisions based on data from distributed, hierarchical sensor nodes.

An additional “device” that was tested successfully with a SmartCore, but not deployed in field trials, is a set of upward- and downward-looking micro-spectrometers in order to examine the possibility of monitoring surface reflectance estimates. The SmartCore was programmed to put together automatically the visible and near-infrared spectral radiance spectra (which come from separate micro-spectrometer heads) and compute the spectral reflectance spectrum from the two radiances (the upward-looking sensors look through a diffuser). Future deployments may also involve the use of webcams, which are expected to contribute both research and pedagogical benefits (Teillet et al., 2001).

Host server, OpenGIS viewer and sensor server software

The ISIES host server was designed and built to receive data from the sensorweb, process them and store them in a relational database. It is the host of a relational database and a file storage system that contains all ISIES data (remote sensing, *in-situ* and GIS). An automated two-way communication module was built to communicate with the SmartCore devices and retrieve the *in-situ* data on a daily basis. It can also receive data and event alerts initiated by the sensorweb and communicated to the server by the SmartCore devices. The output files of this communication module are then parsed and the data are automatically stored in the relational database. A data integration engine was designed and developed to automatically run crop growth models using *in-situ* and remote sensing data to produce biomass and yield maps.

The focus of ISIES OpenGIS components is on interoperability among sensorwebs and their underlying information models. Currently, most research and development on sensorweb or sensor network implementations focus on sensor deployment, sensor communications, and context-specific applications. However, the information model underlying a sensorweb and the interoperability of the model have been rarely addressed. Sensing information is disseminated within each sensorweb using proprietary formats and proprietary communication protocols. Proprietary designs result in poor interoperability among sensorwebs and make collaboration among sensorwebs very difficult.

An *ISIES OpenGIS Viewer* and an *ISIES OpenGIS Sensor Server* have been designed and developed (Liang et al., 2005). These tools deal with information models and interoperability. They link ISIES products (sensor observations, crop yield predictions and biomass predictions) with a global spatial data infrastructure, such as the Global Spatial Data Infrastructure (GSDI) or the Canadian Geospatial Data Infrastructure (CGDI), through open web service interfaces and standard information models for sensors. In order to accommodate various sensors in a sensorweb, standard information models play a vital role by making the whole architecture efficient, extensible, and interoperable. Table 2 lists the information disseminated within a sensorweb and the information that needs to be described in a standard way in order to build an interoperable sensorweb. Users can assemble the interoperable components from different sensorwebs for use in their own applications. These interoperable components include the ability to task sensors, retrieve sensor observations, and utilize processing models within sensorwebs.

The *ISIES OpenGIS Sensor Server* is one of the world's first OGC (Open Geospatial Consortium) Sensor Observation Service (SOS) implementations. It connects to the database of the ISIES host server, accesses ISIES products (e.g., *in-situ* sensing data, remote sensing data, and/or crop growth model results), and serves ISIES products with OGC web service interfaces using the standard-based information models (GML, SensorML, and O&M). A SensorML instance is a self-description of a sensor, which contains sensor specifications, capabilities, geolocation, and history. GML is a standard information model for spatial features. O&M is an information model for observations and measurements, including location and time of measurement, units of measurement, and description of observed phenomenon. Table 3 lists the OGC web service interfaces of the server and descriptions of the interfaces. *ISIES OpenGIS Sensor Server* uses SensorML, GML, and O&M as standard-based information models for sensor information and observations.

ISIES OpenGIS Viewer is built upon an interactive 3D globe client[1]. GSN 3D Globe provides a unified global context within which users can access, visualize and analyze geospatial information from interoperable OGC web map servers (WMS), web coverage servers (WCS) and web feature servers (WFS). In addition to GSN 3D Globe's existing WMS, WCS and WFS functionalities,

[1] GSN 3D Globe, GeoTango International Corp. This name is provided for information purposes only and does not imply any endorsement.

ISIES OpenGIS Viewer supports OGC Sensor Observation Service, SensorML and O&M. When first launched on a desktop computer by a user, the *ISIES OpenGIS Viewer* starts from a "zoomed out" view of the globe and allows the user to select a sensorweb site and "fly into it". While the user is "flying into" the sensorweb site, multi-resolution base maps (e.g., rivers, satellite images) and terrain data are streamed to the viewer via open WMS/WCS/WFS interfaces from various OGC servers (e.g., Natural Resources Canada's WMS Server for Landsat mosaic data). While the user zooms in closer to the site location, the viewer displays high spatial resolution satellite imagery of the site as well as sensorweb nodes with symbols to denote sensor locations. The user can then mouse click on one of the sensor symbols to launch a sensor query dialog to obtain sensing information by spatial-temporal bounding box, sensor type and/or platform type. The user can choose to see query results in three different types of presentation: 1) a temporal plot of *in-situ* observations, 2) ISIES products encoded in GML/O&M, and 3) sensor metadata encoded in SensorML. For example, a user can request a temperature sensor plot as a function of time (Figure 1). A user can also choose to request the GML/O&M encodings of the observations, which contain richer information, such as the observations, units, accuracy, locations, targets of the observations, and the sensor that performed the measurements. The GML/O&M response can direct the user to a detailed description of the sensor in SensorML, which contains the sensor's location, history, capabilities, coordinate reference systems.

Crop growth models

Updated Maas model

Crop growth models are useful for predicting variables like phenology (i.e., developmental stages), foliage characteristics (e.g., leaf area index), total biomass and yield. Model input parameters are related to daily weather conditions (e.g., air and soil temperatures, precipitation, and solar radiation), soil characteristics (e.g., texture and soil available water-holding capacity), crop management (e.g., seeding and harvesting dates), and crop species characteristics. Crop growth models are well suited to the simulation of the temporal variability of a cropping system, where the variability is associated with crop management and climate.

On the other hand, the spatial variability observed at the field level is more complex to describe mathematically because many factors need to be taken into account, such as soil type, drainage, pH, nutrients, compaction, diseases, etc. If those factors have an impact on LAI, then remote sensing images have the potential to characterize this spatial variability. However, the frequency of image acquisition and the analysis of these images are limiting factors for adequate crop growth predictions. In order to characterize these spatial and temporal variabilities, the remote sensing and crop modelling approach developed by Maas (1988a,b, 1992, 1993a,b,c) for cereals, like sorghum, corn, and wheat, and rendered in the Fasmod Fortran code, was adopted to model spring wheat in ISIES. This approach uses, as input to the crop growth simulator, weather data, crop phenology information and LAI obtained from crop measurements in the field or from remote sensing estimations, which facilitates the incorporation of both temporal and spatial variabilities.

As part of the ISIES project, the Fasmod Fortran code was updated to Visual Basic (FasmodVB). The crop growth module in this code is relatively simple and offers excellent possibilities for adaptation to different crops. An optimization technique is used for within-season calibration of leaf area index prediction with the field crop observations. Results for spring wheat (not presented here) indicate the following limitations in the prediction of crop phenology and in the within-season estimation of initial parameters by mathematical optimization: i) the phenology module is not really used in a predictive mode since dates of specific phenological events are required as inputs to the model; ii) the model predicts green or live LAI (Maas, 1993a), whereas available field measurements are usually total LAI, which includes the senescing leaves; and iii) the algorithms related to leaf senescence simulation seem to create instabilities in LAI predictions.

Updated Versatile Soil Moisture Budget model

The importance of soil water in agriculture has long been recognized (e.g., Ritchie, 1988). Crop growth and yields are perhaps more closely related to soil water than any other single meteorological element, including rainfall. Consequently, estimating soil water status is an important component of crop yield modeling, especially in the semi-arid regions of the Canadian Prairies (Hanks and Ritchie, 1991).

The Versatile Soil Moisture Budget (VSMB) model, as developed by Baier et al. (1979), calculates the soil water balance within the rooting depth of the crop from precipitation, evapotranspiration and deep drainage data (Akinremi et al., 1996). Water is withdrawn simultaneously, but at different rates, from different zones (depths) in the soil profile, depending on the rate of potential evapotranspiration, the stage of crop development, the water release characteristic of the soil and the available water content of the soil.

The major limitation of this model is that it does not estimate biomass accumulation throughout the growing season. The relationship between end-of-season biomass and water use (i.e., accumulated actual evapotranspiration between the start and the end of the growing season) was based on native rangeland data collected during 1968 - 1971 at Matador, Saskatchewan (Coupland, 1973). Combined with this relationship, the VSMB model was further modified to predict end-of-season biomass using currently local (i.e., on site) available weather data (i.e., up to a given date within the simulation year) and historic long-term (1971 - 2000) weather data from Brooks, Alberta.

Test sites

Two contrasting test sites, annual cropping and rangeland, were selected in southern Alberta. The annual crop site located near Lethbridge (Latitude 49^{o}43$'$ N, Longitude 112^{o}48$'$ W, Elevation 937 m ASL) represents a dry land zero-till management system. The test crop was wheat. As the crop rotation is typically a cereal-broadleaf, two adjacent fields of approximately 250 ha each were used to obtain data for two years of wheat.

The rangeland study site was at Antelope Creek Ranch (Latitude 50^{o}37’ N, Longitude 112^{o}10’ W, Elevation ~780 m ASL), approximately 15 km west of Brooks, Alberta. Established in 1986, Antelope Creek Ranch is a multi-disciplinary, multi-agency research site. The ISIES study focused on three native grassland fields (each ~450 ha in size) on the ranch, which were in a deferred, rotational grazing pattern. The vegetation represents the *Stipa-Bouteloua-Agropyron* community of the mixed grass prairie ecoregion. Annual precipitation in the area averages 340 mm, with 240 mm falling from April-August; average temperatures range from -12.5 ^{o}C in January to 18.4 ^{o}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 glacial 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.

Data collection

Sensorweb datasets

Figure 2 presents a schematic of the sensorweb layouts at the two test sites in 2004. The crop site had one “soil moisture patch”, whereas the larger Antelope Creek site had three. Each soil moisture patch was 100 m long and contained three sensor nodes that communicated via short-range RF to one SmartCore. Each sensor node encompassed an area of approximately 25 m by 25 m and included multiple sensors (at least five). These nodes had a mix of mostly surface soil moisture probes (Decagon Echo probes) and a few Decagon soil temperature probes and Decagon precipitation gauges. In particular, the configuration was such that five individual sensors were hard-wired to a radio transceiver, which communicated by RF with the SmartCore nearest to that soil moisture patch. All soil moisture patches also had one or more sets of sensors deployed vertically in the ground to capture a depth profile of soil moisture. Additional Decagon precipitation nodes and weather nodes (Hobo and Campbell Scientific stations) rounded out the complement of data acquired at each test site. The weather nodes obtained soil moisture and temperature, air temperature and pressure, relative humidity, precipitation, wind speed and direction, and photosynthetically active radiation to complement the data acquired at the soil moisture patches.

Detailed descriptions of the many sensorweb datasets collected during 2004 and 2005 field seasons are beyond the scope of this overview paper and not reported here. Collectively, the ISIES sensorweb datasets consisted of soil moisture and temperature, air temperature and pressure, relative humidity, precipitation, wind speed and direction, and photosynthetically active radiation. These variables, relevant to agriculture, were measured using three types of sensor nodes: soil moisture patches, precipitation nodes, and weather nodes. This three-part distinction of sensor node types arose from the different spatial sampling requirements for accurate weather (10-25 km), precipitation (0.1-1 km), and soil moisture measurements (1-10 m), respectively. Temporally, as a rule, all measurements were made every hour throughout the growing seasons in 2004 and 2005.

While the weather and precipitation nodes made measurements at single points in space, the soil moisture patch was designed to acquire multiple soil moisture measurements over an area. This was required because of the high spatial variability of soil moisture and the impact of speckle in the

C-band SAR images used for soil moisture estimation. These soil moisture measurements were made in the surface layer (0-5 cm). Soil moisture was also sampled vertically (at six depths between the surface layer and a depth of approximately 1 m) at a small subset of these locations.

For proof-of-concept demonstration, the following simple event monitoring rules were implemented in SmartCore (and tested successfully in trial mode only): send event notification if more than 25 mm of rain fall in a rolling 24 hour period; send event notification if the soil temperature remains below 10 ^{o} C for a rolling 24 hour period; send event notification if the soil moisture stays above 35 % for a rolling 24 hour period.

Remote sensing datasets

Several types of remote sensing images were acquired over the two test sites, including imagery from CHRIS, the Envisat Advanced Synthetic Aperture Radar (ASAR), the Radarsat-1 SAR, Quickbird and the Envisat Medium-Resolution Imaging Spectrometer (MERIS). In this research and development project, the main source of optical hyperspectral imagery was the CHRIS sensor, whereas Envisat ASAR imagery was used to allow testing of new algorithms presented in the literature for LAI (Haboudane et al. 2004) and soil moisture (Wigneron et al., 2003) extraction, respectively. LAI maps were generated from cloud-free CHRIS imagery. The ASAR imagery was calibrated and geo-referenced. Soil moisture maps were produced based on the combination of satellite radar imagery and *in-situ* measurements.

CHRIS is a hyperspectral sensor developed by Sira electro-optics. The spectral range is 0.4 to 1.05 µm encompassing up to 63 spectral bands. The spectral sampling ranges from 2-3 nm in the blue to 12 nm at the shortwave infrared. The spatial ground resolution is 34 m. The PROBA platform allows both along-track and across-track pointing of the CHRIS sensor. CHRIS data were chosen for several reasons. The spectral bands are close to those of the Compact Airborne Spectrographic Imager (CASI) used during the development and testing of the LAI algorithms. The pointing capabilities of PROBA enabled the collection of a greater number of images during the growing season than potentially available from most other sensor systems. CHRIS data were also delivered in a very timely manner after data acquisition.

Other measurement datasets

Plant biophysical data were acquired at test sites during the course of the growing season to characterize growth and provide verification data for (a) the remote sensing derived LAI products and (b) the crop growth models that predict crop phenology and above-ground biomass.

Products

Comprehensive datasets of *in-situ* data (weather, soil, biomass and more), remote sensing data (optical and SAR), Geographic Information System (GIS) data and ancillary data, such as actual crop yield, were put together for each of the 2004 and 2005 field seasons. The remote sensing data were used by ISIES to generate leaf area index maps and soil moisture maps. Examples of these products are presented in the following paragraphs. Comparisons with ground-based measurements are in progress. These maps together with *in-situ* data were then used with the vegetation models to produce biomass maps and yield predictions.

Leaf area index maps

The nadir view CHRIS image layer was extracted and atmospherically corrected using the CAM5S radiative transfer code (O'Neill et al., 1996), with aerosol optical depths provided by the Networked On-line Mapping of Atmospheric Data (NOMAD) database maintained by the University of Sherbrooke (O'Neill et al., 2002). LAI was retrieved using the Modified Triangular Vegetation Index (MTVI2) (Haboudane et al., 2004):

$$MTVI2 = \frac{1.5*(1.2*(R_{800}-R_{550})-2.5*(R_{670}-R_{550}))}{\sqrt{(2*R_{800}+1)^2-(6*R_{800}-5*\sqrt{R_{670}})-0.5}} \quad . \qquad (4)$$

$$LAI\ \ MTVI2 = 0.2227*\exp(3.6566*MTVI2)\ . \qquad (5)$$

The coefficients in equation (5) were derived from simulated data and then validated using real imagery of corn, wheat and soybean (Haboudane et al., 2004). As a product example, Figure 3 shows a 2004 time series of LAI maps derived from CHRIS imagery acquired over the spring wheat field (Smith et al., 2005).

Soil moisture maps

During the 2004 season, 11 multi-angle, dual-polarization (horizontal-horizontal (HH) and vertical-vertical (VV)) Envisat ASAR images were collected over Antelope Creek Ranch. The ASAR data were calibrated and co-registered, and then used as input to a Bayesian estimator that uses time series information to estimate surface soil moisture (Haddad et al., 1996). In particular, the estimator optimally integrates all available information, including the multi-polarization and multi-angle SAR measurements, the knowledge of radar backscatter behaviour, and coarse a-priori knowledge of the surface roughness and soil moisture in the area. As a product example, Figure 4 shows a map of estimated surface soil moisture for the Antelope Creek Ranch area derived from ASAR imagery acquired in 2004.

Biomass and yield prediction maps

ISIES estimated biomass and predicted yield for the test sites on the same pixel grid as the CHRIS imagery. The maps were geo-corrected and rendered both as a raster-based image and as a vector-based map. A description of these products is beyond the scope of this overview paper; they will be discussed in greater detail in a follow-on paper.

Concluding remarks

A prototype *in-situ* sensorweb was successfully designed, developed, deployed and operated in a crop application setting. Innovations include the SmartCore device, advanced crop growth models, and automated *in situ* and remote sensing data integration and modeling. Moreover, the user interaction with these mainly autonomous systems is via one of the world's first sensorweb-enabled OpenGIS-compliant web service systems. Output products include maps of leaf area index, soil moisture and biomass, as well as crop yield predictions.

Earth science sensorweb data have the potential to become an integral part of decision support domains. The work reported in this paper has taken an initial step towards demonstrating approaches to the time-critical and cost-effective monitoring of complex and dynamic systems. Nevertheless, much more needs to be done to provide a more solid basis for decision support, including smaller, smarter and cheaper sensor systems for monitoring, the integration of time-critical *in-situ* sensor data and/or metadata into on-line geospatial data infrastructures, and the generation of validated data and information products derived from the fusion (physically self-consistent integration) and assimilation of *in-situ* and remote sensing data into models. Ongoing challenges in such endeavours are the early developmental stages of the rapidly advancing technologies involved, the lack of resources to put in place capabilities for integrated assessment, and the potential future shortfall of highly qualified science and technology personnel.

The ISIES trials revealed that currently available advanced technologies have the potential to assess agricultural conditions. However, pending further miniaturization and cost reductions arising from micro-electro-mechanical systems (MEMS) technology and nanotechnology, the cost of populating sensorwebs throughout a region remains a challenge even though the individual components are fairly inexpensive. The implication is that, for now, sensorweb technology is more likely to be deployed in a small area or region to acquire information that can be used to validate satellite retrievals and/or as a guide to generate forecasts on crop or rangeland conditions over a larger region where growing conditions, weather, soils and crops are fairly homogeneous.

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List of Acronyms

ASAR	Advanced Synthetic Aperture Radar
ASL	Above Sea Level
CASI	Compact Airborne Spectrographic Imager
CGDI	Canadian Geospatial Data Infrastructure
CHRIS	Compact High-Resolution Imaging Spectrometer

ESA	European Space Agency
GEOSS	Global Earth Observation System of Systems
GIS	Geographic Information System
GML	Geographic Mark-up Language
GSDI	Global Spatial Data Infrastructure
HH	Horizontal-Horizontal
I2C	Inter Integrated Circuit
I/O	Input/Output
ISIES	Intelligent Sensorweb for Integrated Earth Sensing
LAI	Leaf Area Index
MDA	MacDonald Dettwiler and Associates
MDT	Mountain Daylight-saving Time
MEMS	Micro-Electro-Mechanical Systems
MERIS	Medium Resolution Imaging Spectrometer
MTVI2	Modified Triangular Vegetation Index 2
NOMAD	Networked On-line Mapping of Atmospheric Data
O&M	Observations and Measurements
OGC	Open Geospatial Consortium
PN	Precipitation Node
PROBA	Project for On-Board Autonomy
RF	Radio Frequency
RS232	RETMA (Radio Electronics Television Manufacturers Association) Standard 232
SAR	Synthetic Aperture Radar
SensorML	Sensor Model Language

SOS	Sensor Observation Service
SP	Soil-moisture Patch
SPI	Serial Peripheral Interface
TCP/IP	Transmission Control Protocol/Internet Protocol
UK	United Kingdom
VSMB	Versatile Soil Moisture Budget
VV	Vertical-Vertical
WCS	Web Map Servers
WFS	Web Feature Servers
WMS	Web Coverage Servers
WN	Weather Node
XML	Extensible Mark-up Language

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Table Captions

Table 1. List of SmartCore device functionalities.

Table 2. Information disseminated within a sensorweb.

Table 3. Web service interfaces of *GeoSWIFT Server*.

Figure Captions

Figure 1. Air temperature measurements displayed in the *ISIES OpenGIS Viewer*.

Figure 2. Schematic sensor node distribution at each test site. The SmartCore devices are co-located with the weather nodes.

Figure 3. Time series of leaf area index (LAI) products derived from CHRIS imagery acquired over the spring wheat test site in 2004. The spring wheat field is outlined by the rectangle.

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Table 1. List of SmartCore device functionalities.

SmartCore Functionalities	
Communications	*Power Management*
Support dial-in modem connection	Remotely configurable awake/sleep period
Support direct serial connection	Power monitoring and automatic shutdown
Support dial-out modem connection	Remotely power activation and shutdown
Hardware	*Sampling*
5 separate serial connections	Remotely configurable device sampling period
5 (jumper) selectable 7- or 12-volt switches	New drivers for virtual devices
15 analog to digital converters	Remotely configurable device list
Dual purpose reset button (to force clean boot)	In-field sensor data aggregations (time and space)
Battery back-up real time clock	Spectrometer reflectance calculation
Event Monitoring	On-demand device sample acquisition
Remotely configurable events	
Automatic event notification	

Table 2. Information disseminated within a sensorweb.

Types of Information	Examples
Sensor metadata	Capabilities, manufacturers, histories, owners
Sensor observations	Scalar values, aggregated values
Units of the observations	Degrees Celsius/Fahrenheit and conversion formulae
Calibration formulae	Soil moisture calibration factors
Geophysical variables	Air temperature, soil moisture content
Associated sensor features	Road network intersection of a traffic webcam location
Locations	Sensor locations, static, mobile, coordinates

Table 3. Web service interfaces of *GeoSWIFT Server*.

Requests	Responses
GetCapabilities	The GetCapabilities request XML response conforms to OGC service information model schema and provides detailed information for a client to access the service. The information provided includes service type, service instance, content type, and content instance.
GetObservations	The GetObservations request XML response is encoded conforming to GML and O&M schema. It contains values, units and locations of the requested sensor observations.
DescribePlatform	The XML response describes the sensor platform and conforms to SensorML schema. An example of a sensor platform can be an aircraft platform that carries a camera, several inertial sensors and meteorological sensors.
DescribeSensor	The XML response contains detailed information on sensor characteristics encoded in SensorML. The sensor characteristics can include lists and definitions of observables supported by the sensor.

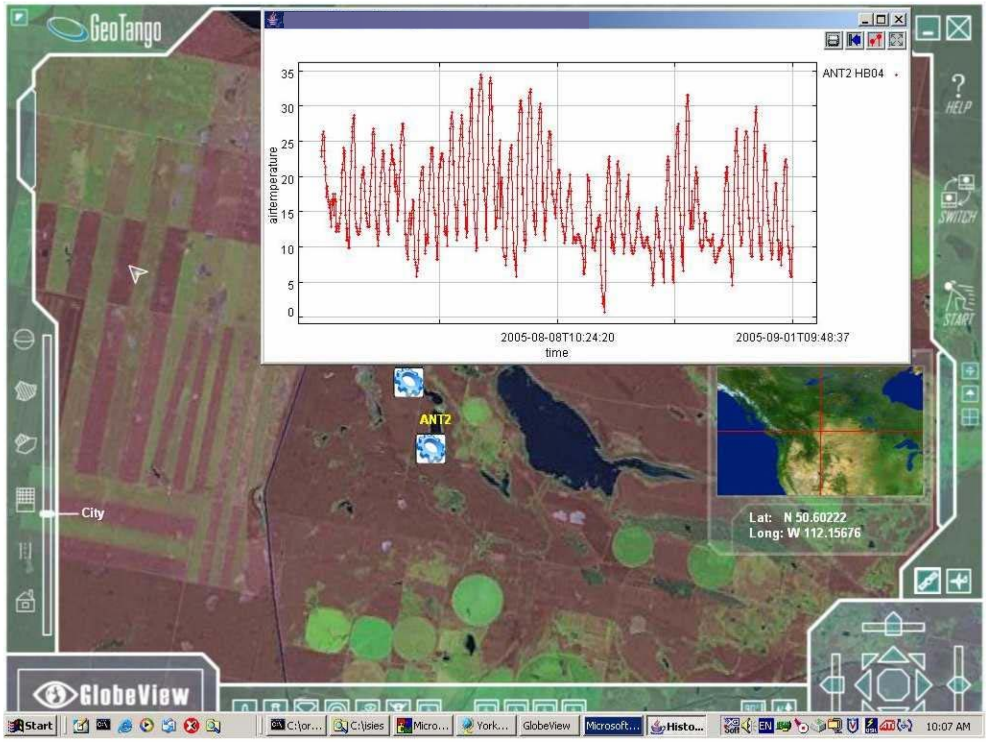
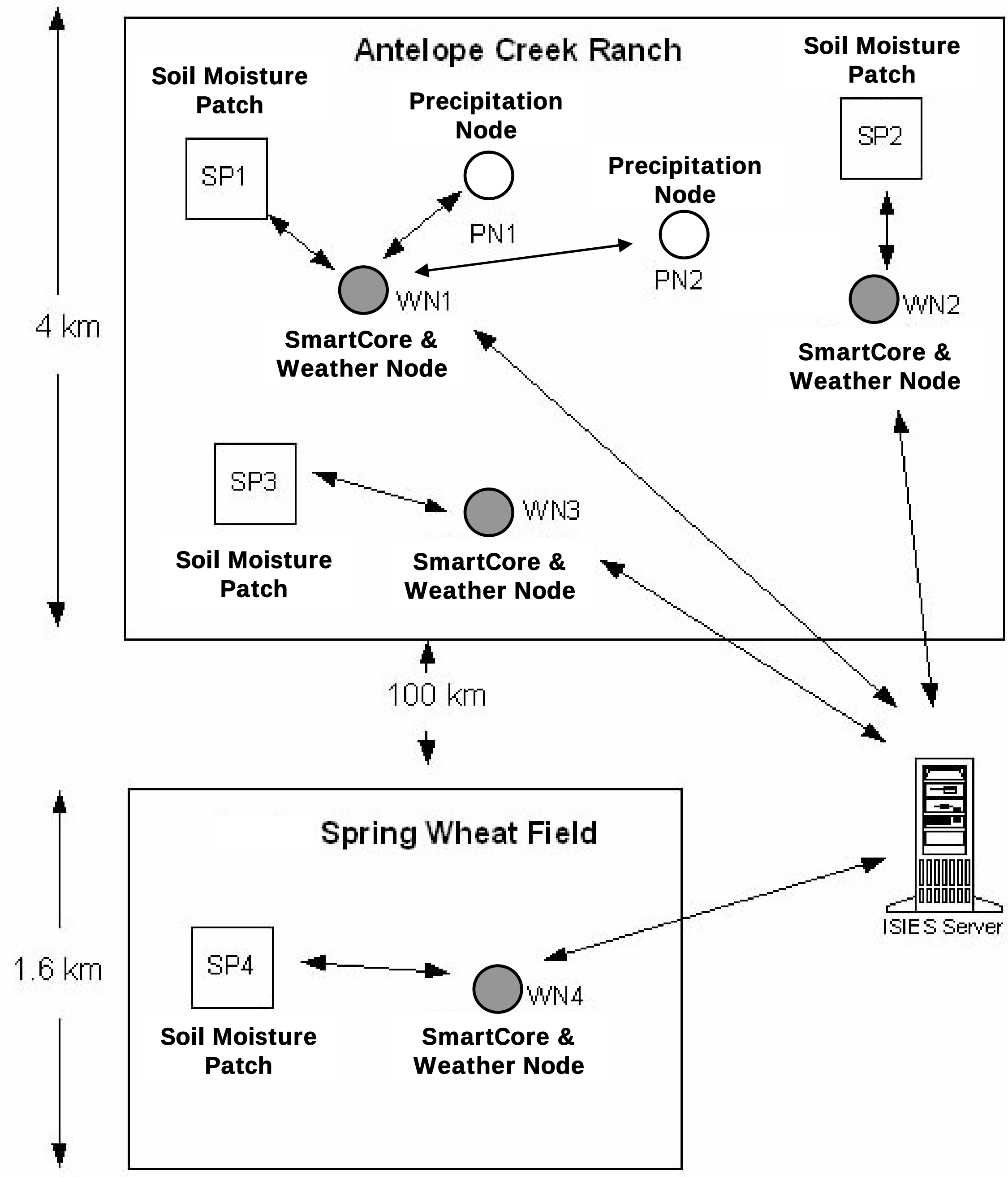


Figure 1. Air temperature measurements displayed in the *ISIES OpenGIS Viewer.* Air temperature is in degrees Celsius and the time zone was Mountain Daylight-saving Time (MDT).



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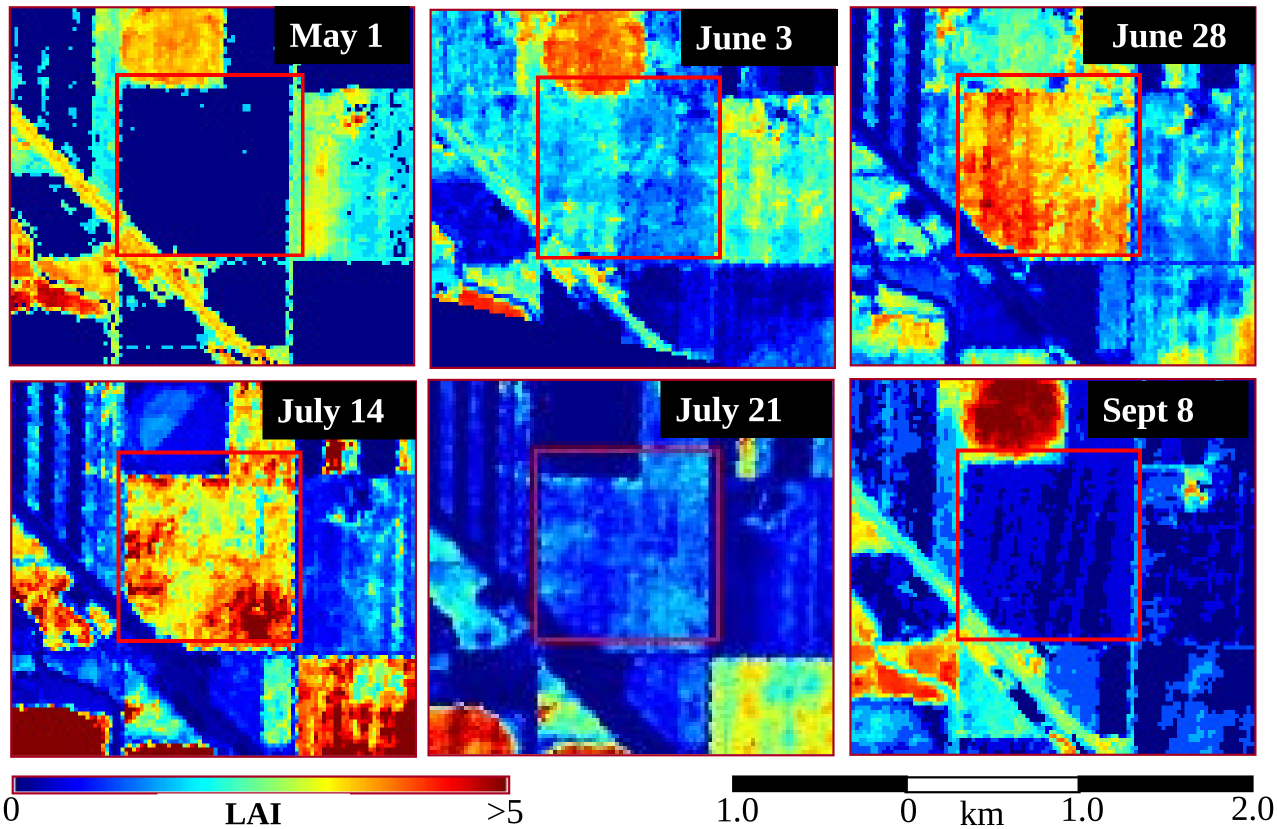

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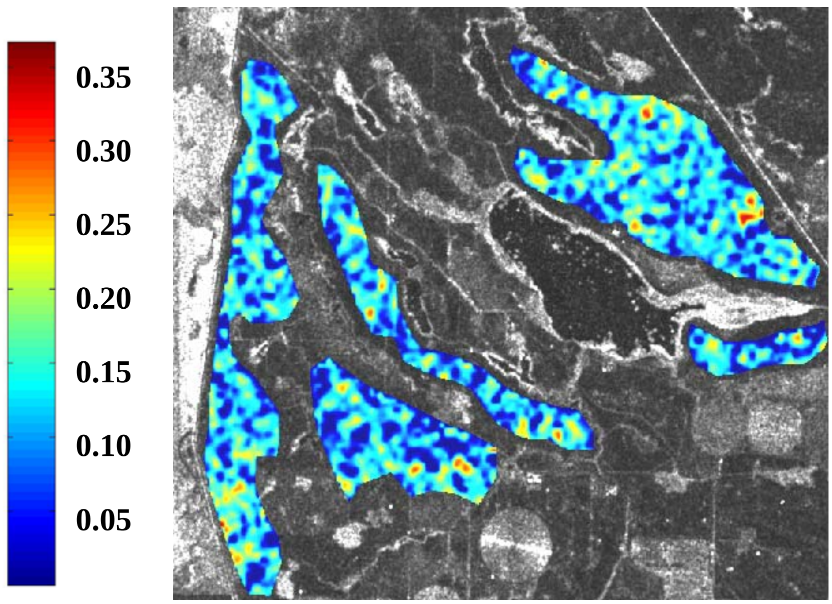

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