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Systems Assessment of Water Savings Impact of Controlled Environment Agriculture Utilizing Wirelessly Networked Sense•Decide•Act•Communicate (SDAC) Systems

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Abstract

Reducing agricultural water use in arid regions while maintaining or improving economic productivity of the agriculture sector is a major challenge. Controlled environment agriculture (CEA, or, greenhouse agriculture) affords advantages in direct resource use (less land and water required) and productivity (i.e., much higher product yield and quality per unit of resources used) relative to conventional open-field practices. These advantages come at the price of higher operating complexity and costs per acre. The challenge is to implement and apply CEA such that the productivity and resource use advantages will sufficiently outweigh the higher operating costs to provide for overall benefit and viability. This project undertook an investigation of CEA for livestock forage production as a water-saving alternative to open-field forage production in arid regions. Forage production is a large consumer of fresh water in many arid regions of the world, including the southwestern U.S. and northern Mexico. With increasing competition

among uses (agriculture, municipalities, industry, recreation, ecosystems, etc.) for limited fresh water supplies, agricultural practice alternatives that can potentially maintain or enhance productivity while reducing water use warrant consideration.

The project established a pilot forage production greenhouse facility in southern New Mexico based on a relatively modest and passive (no active heating or cooling) system design pioneered in Chihuahua, Mexico. Experimental operations were initiated in August 2004 and carried over into early-FY05 to collect data and make initial assessments of operational and technical system performance, assess forage nutrition content and suitability for livestock, identify areas needing improvement, and make initial assessment of overall feasibility. The effort was supported through the joint leveraging of late-start FY04 LDRD funds and bundled CY2004 project funding from the New Mexico Small Business Technical Assistance program at Sandia.

Despite lack of optimization with the project system, initial results show the dramatic water savings potential of hydroponic forage production compared with traditional irrigated open field practice. This project produced forage using only about 4.5% of the water required for equivalent open field production. Improved operation could bring water use to 2% or less. The hydroponic forage production system and process used in this project are labor intensive and not optimized for minimum water usage. Freshly harvested hydroponic forage has high moisture content that dilutes its nutritional value by requiring that livestock consume more of it to get the same nutritional content as conventional forage. In most other aspects the nutritional content compares well on a dry weight equivalent basis with other conventional forage. More work is needed to further explore and quantify the opportunities, limitations, and viability of this technique for broader use. Collection of greenhouse environmental data in this project was uniquely facilitated through the implementation and use of a self-organizing, wirelessly networked, multi-modal sensor system array with remote cell phone data link capability. Applications of wirelessly networked sensing with improved modeling/simulation and other Sandia technologies (e.g., advanced sensing and control, embedded reasoning, modeling and simulation, materials, robotics, etc.) can potentially contribute to significant improvement across a broad range of CEA applications.

Acknowledgements

We wish to thank Dr. Enrique Sanchez and Mr. Bill Wallace of Union Ganadera Regional de Chihuahua for providing the host site for this project at the Santa Teresa Livestock Border Crossing Facility. We also wish to thank Dr. Hector Leon Gallegos of the State of Chihuahua for encouragement and advice. Thanks also go out to the following New Mexico small business participants for their interest: Sierra Irrigation, NM Wool Growers Association, NM Cattle Growers Association, Mesilla Valley Feeds, Santa Teresa Livestock Border Crossing (Union Ganadera Regional de Chihuahua), Pollo Real, and G&L Contract Management.

We especially wish to thank Gerry Yonas, Sandia VP, Principal Scientist, and leader of the Advanced Concepts Group, and Bob Eagan, former VP of Energy and Critical Infrastructure at Sandia for their encouragement and funding support for this project. In addition we wish to thank Vic Chavez and Mariann Johnston from Sandia's Office of Advocacy and Small Business Development for their financial support under the New Mexico Small Business Technical Assistance Program.

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Nomenclature

ACG	Advanced Concepts Group
ADC	Analog-to-Digital converters
ADF	Acid Detergent Fiber
AF	Acre-feet
CEA	Controlled Environment Agriculture
CEAC	Controlled Environment Agriculture Center, University of Arizona, Tucson
CP	Crude Protein
DHS	Department of Homeland Security
DM	Dry Matter
DoD	Department of Defense
DoE	Department of Energy
DP	Dew Point
E&CI	Energy and Critical Infrastructure
GDP	Gross Domestic Product
GNU	Recursive acronym for “GNU’s Not Unix” re/ GNU/Linux OS software
ISHS	International Society of Horticultural Sciences
LDRD	Laboratory Directed Research and Development
LED	Light Emitting Diode
Mote	Small, integrated sensor system with wireless communications
NDF	Neutral Detergent Fiber
NesC	Programming Language for Deeply Networked Systems (Extension of C)
NMSBA	New Mexico Small Business Assistance
NMSU	New Mexico State University
OS	Operating Systems
PAR	Photosynthetic-Active Radiation
RH	Relative Humidity
RHO^2 (ρ^2)	Correlation Coefficient
Sandia	Sandia National Laboratories
SDAC	Sense, Decide, Act, & Communicate Systems
SECDED	Single Error Correction and Double Error Detection
T	Temperature
TDF	Total Digestible Nutrients
TinyOS	Operating system software developed by UCB for motes
U of A	University of Arizona
UC Berkley	University of California Berkley
UCB	University of California at Berkeley
UCLA	University of California Los Angelis
USDA	United States Department of Agriculture
UTEP	University of Texas El Paso
WN	Water & Nutrient Application

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1 Introduction

This report describes a project undertaken in late-FY04 to investigate the practicality and water savings potential of growing livestock forage in arid regions using controlled environment agriculture (CEA) techniques as an alternative to conventional open field approaches. The project was specifically focused on investigating the operational performance of a passive (no active heating or cooling) and relatively low-technology plastic greenhouse system developed and used in Chihuahua, Mexico for growing livestock forage hydroponically (i.e., without soil) with significantly reduced water use in draught-stricken areas of the state [1].

Controlled Environment Agriculture (CEA) refers to the practice of growing plants or crops in "protected" environments under relatively controlled conditions, which may or may not involve the use of soil as the growing medium and support matrix for the plant roots. Hydroponics (growing plants without soil) is often used in CEA to provide better control of nutrients and root-zone growing conditions. For the sake of this discussion, we apply the term CEA rather loosely to a range of structures and systems that span simple "protective" enclosures like passive plastic tunnel or hoop houses, to more sophisticated plastic and glass greenhouse systems with active environmental controls. At the extreme end of the spectrum are sophisticated growth chambers and habitat systems with artificial lighting and active, closed-cycle environmental control, waste stream management, and recycling. Applications of CEA range from extending the growing season of soil-based horticultural crops, to large-scale commercial hydroponic greenhouse production of fresh high-value products like vine-ripened tomatoes, to chambers for growing lettuce and other fresh vegetables for people in extreme environments like the South Pole or in space [2-3].

CEA is a more intense and technically-orientated form of agriculture than conventional open-field practice. On a per-acre basis, CEA is more expensive, labor intensive, and usually requires a higher level of operational expertise than conventional farming. For this reason it is more difficult to execute successfully and has higher associated risks. Conversely, it can provide significantly greater productivity and resource use efficiency. This means more productive output for a given crop with significantly less water use on a per-acre basis. When properly done, it can also provide increased crop product reliability and quality due to less susceptibility to adverse weather events, drought, disease, and pests. This can help reduce or, in some cases eliminate, the need for pesticide use, and can reduce environmental impacts associated with pesticide and fertilizer contamination of water, land, and related ecosystems. CEA is also modular, scaleable, and does not require high-quality arable land when hydroponics is used.

CEA has largely been developed and used outside the U.S. for production of high-quality crops of relatively high value (flowers, fresh vegetables, transplants, etc.). It also provides the means for extending growing seasons in colder climates [4-5]. Due to the historic abundance of water, fertile land, and temperate growing conditions over broad geographic areas, there has been little incentive or need in the past for the U.S. to pursue CEA. This is slowly changing in the U.S. for high-value crops. CEA-related

research, development, and technical training in the U.S. is primarily being done in a limited number of agricultural university programs (e.g., University of Arizona in Tucson: http://ag.arizona.edu/ceac).

There is increasing need world-wide to improve agricultural productivity, along with water and land use efficiency, in ways that can be more sustainable with less environmental impact while enhancing economic development. As these pressures rise, developing improved CEA systems that are appropriate and easier to successfully adapt for a broader range of conditions and user capabilities could make a significant contribution. This demands better understanding and management of key biophysical processes and environmental interactions. It also requires improvement in systems design, implementation, operation, sensing, monitoring, control, training, and decision-support. In many of these areas, CEA could benefit from the "dual-use" of various Sandia technologies and capabilities being developed and applied in support of DoE, DoD, and DHS mission areas. Examples include advanced sensor technologies and systems, modeling and simulation of complex dynamic systems, embedded reasoning and decision-support, adaptive response, advanced materials, automation, robotics, physical security, energy systems, water treatment, and others.

Wirelessly-networked and embedded sensor/responder systems [6-7] are a specific class of emerging technologies that could make significant contribution toward improving CEA. Sandia's Advanced Concepts Group refers to this class of technologies as networked *Sense, Decide, Act, and Communicate (SDAC) systems* [8-9]. SDAC networks are of interest to Sandia and others as a possible enabler of transformational capabilities in future military, intelligence, and homeland security applications. To investigate the potential for SDACs to improve CEA performance, this project has initiated the use of wirelessly networked sensor technology for environmental monitoring that could lead to improved CEA system awareness, control, and decision-support. Migration toward wirelessly networked SDAC systems is a logical extension of current techniques used for sensing and control in CEA [10-14]. To our knowledge, this project is the first application of self-organizing wirelessly networked multi-modal sensing in CEA.

1.1 Background and Motivation

Water and agriculture are highly interdependent and critical to the well-being, economy, and security of most societies. Irrigated agriculture is the major consumer of fresh water supplies in many parts of the world, particularly in relatively arid regions like the southwestern U.S. and northern Mexico. Irrigated crop agriculture in New Mexico uses 75% of total annual state water withdrawls, over half of which goes toward production of forage crops. State forage production alone in 2002 utilized 380,000 acres of land and on the order of 1-million acre-feet (AF) of water [15], as illustrated in Figure 1-2. Irrigated forage production is a major consumer of fresh water in the western U.S., Mexico, and many other arid regions globally. As population and industrial development grows, competition for limited water supplies will only increase among competing uses (municipal, industrial, agricultural, recreation, ecosystems, etc.).

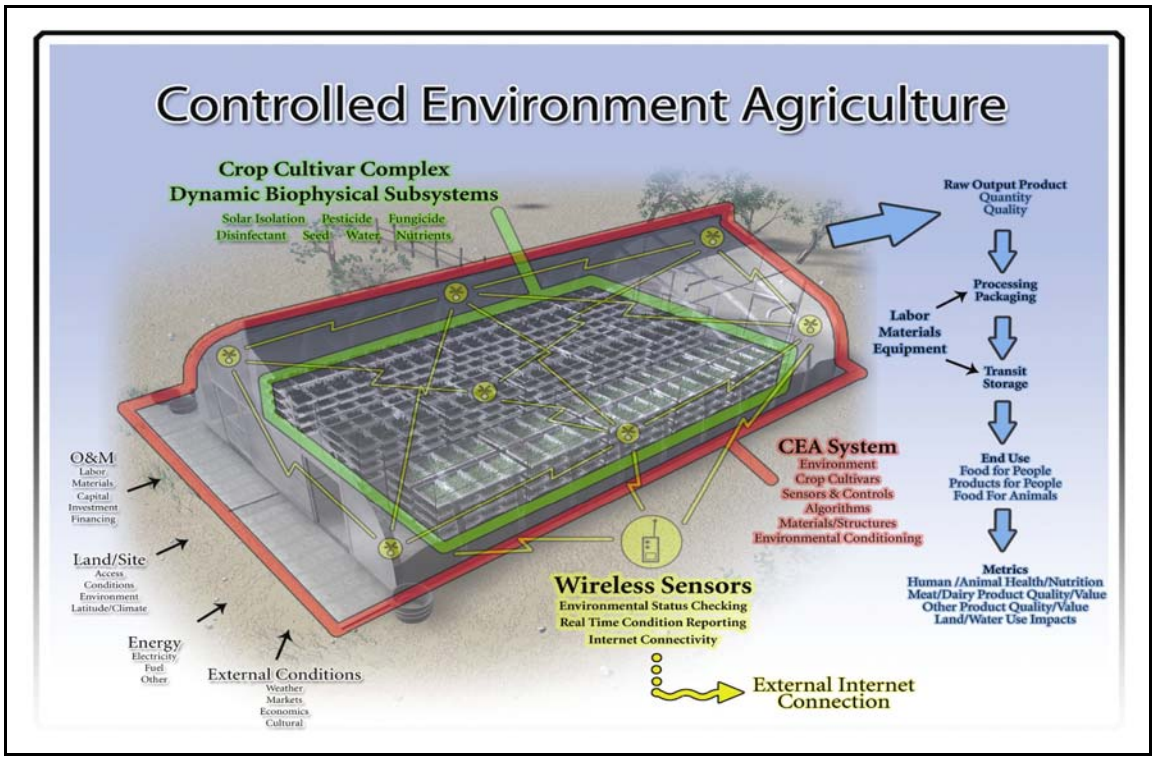

Figure 1-1 Overview of CEA Forage Project Systems Approach and Issues.

Scarcity of adequate fresh water supplies is a global concern, particularly in more arid regions, as indicated in Figure 1-3 [16]. Climate change is a wildcard issue that could exacerbate problems with the highly interdependent intersection of water, energy, and agriculture [17-18]. Methods and technologies that can contribute to improved water use efficiency and productivity merit closer consideration.

Pioneering work recently began in Chihuahua to develop and deploy a water-saving hydroponic greenhouse approach for forage production in support of livestock producers in water-stressed areas of the state. Sandia National Laboratories began to investigate this in FY03 as an interesting technique to consider for reducing agricultural water usage in New Mexico and the greater southwestern region. This approach would also be of interest for other arid regions of the world, and could perhaps contribute to more sustainable and secure livestock production in water-stressed regions [19].

1.2 Project Purpose and Objectives

The purpose of this project was to initiate investigation of controlled environment agriculture as a water-saving alternative to water-intensive open-field irrigated agriculture in arid regions. Initial focus was placed on the production of livestock forage as a major water consumer. The objective was to experimentally evaluate the operational performance of the hydroponic forage production system developed and used in Chihuahua, Mexico. Included was evaluation of the nutrition content and suitability of the hydroponic forage product for livestock feed. We also introduced the use of wirelessly-networked sensor system technology to evaluate its potential for improving environmental monitoring and control of CEA system performance.

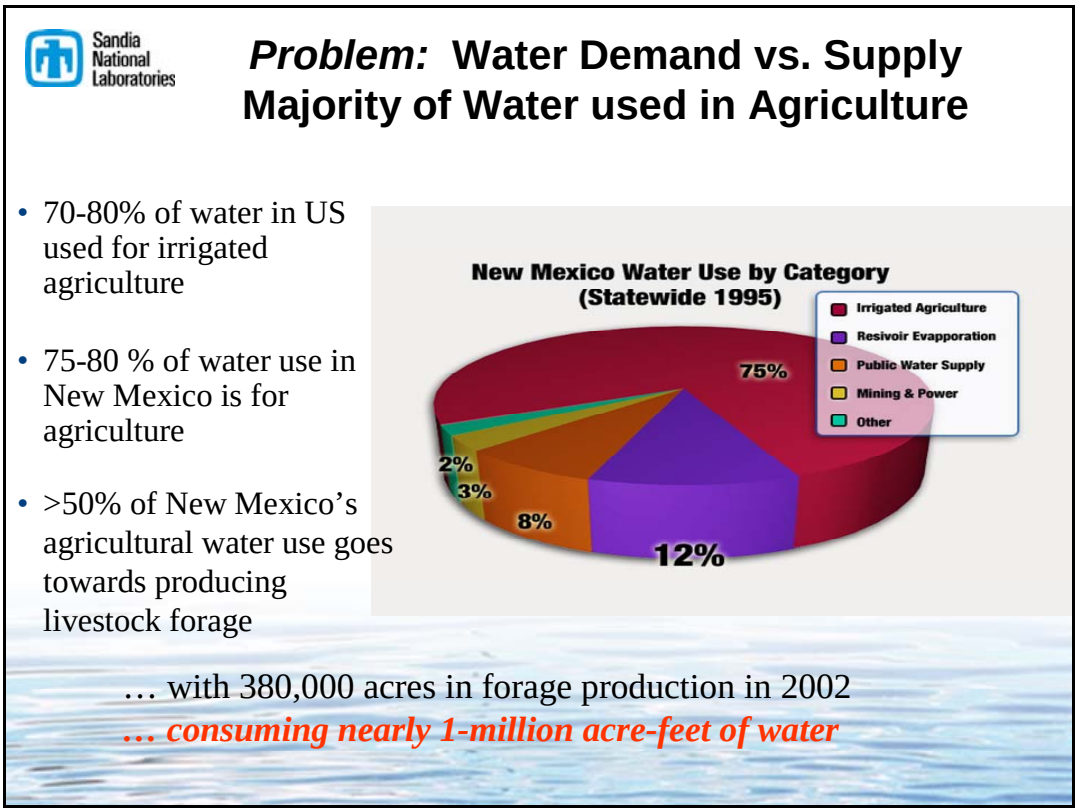

Figure 1-2 Water use in New Mexico, with forage production predominating.

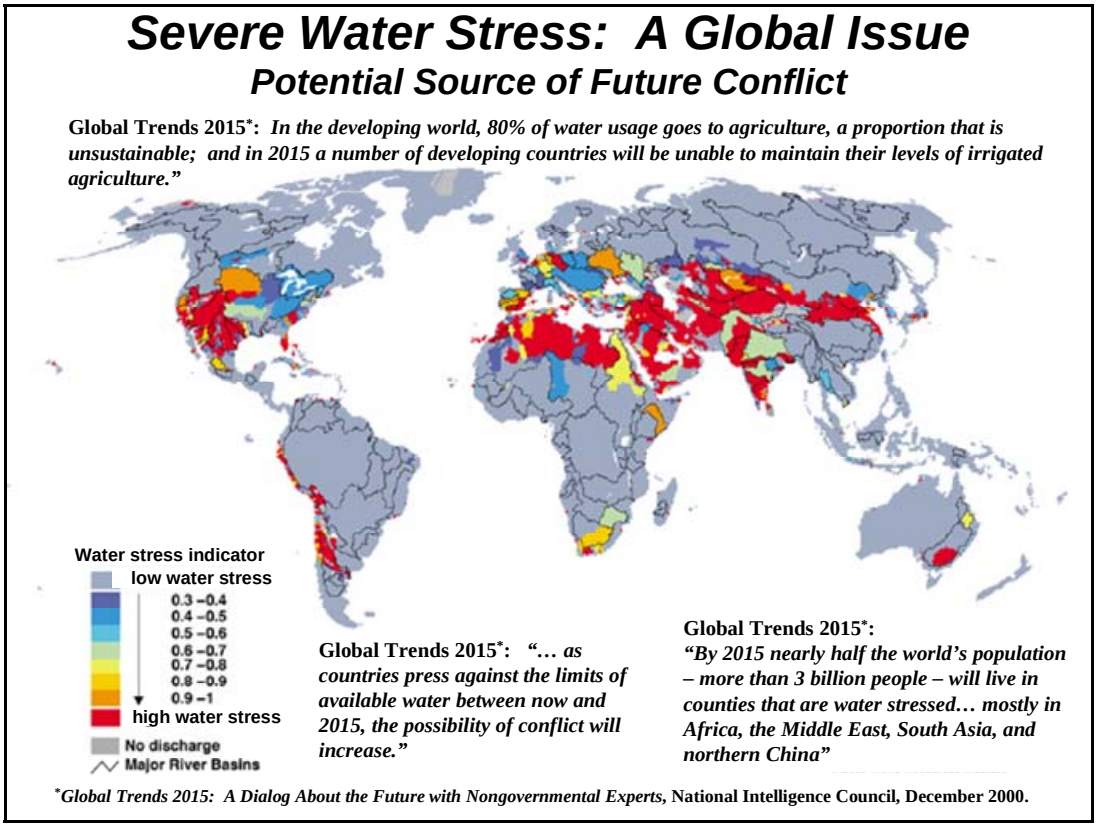

Figure 1-3 Water stress: A global issue and potential source of conflict.

The challenge is to broaden CEA's practical applicability and contribution to water-savings in agriculture through improved systems design and implementation, performance optimization, and decision-support. The proposed project will begin to address this by investigating the operational performance of CEA for forage production.

Numerous technical, economic, social, cultural, legal, and policy issues will impact whether CEA forage production can be an acceptable and cost-effective alternative to current open-field practice. The future availability and cost of water, and the governing water-use policies, will be major determinants of the economic viability of CEA for forage production. However, the potential orders-of-magnitude savings in water and land usage for forage production with CEA warrants further investigation in light of increasing water scarcity and competition among user groups in arid regions. The trend toward global expansion of livestock production is also expected to put increasing and unsustainable demand and strain on agricultural land and water resources required for conventional forage [19].

1.3 Technical Approach

The approach taken for the hydroponic forage project is summarized as follows:

- Build an operational facility based on a system developed in Chihuahua
- Consult with Chihuahua and UofA CEA experts
- Establish daily on-site support with UTEP interns
- Monitor and quantify resource use (water, seed, labor, etc.,) and evaluate operational performance
- Use various types of seed to compare and contrast growth and nutritional performance
- Assess nutrition content through livestock nutrition specialists at NMSU
- Introduce the use of wireless sensor network for environmental monitoring
- Make preliminary assessment of performance based on project operations
- Identify future directions and needs

1.4 Document Overview

The remainder of this report begins in Section-2 with an overview of the hydroponic forage production process. This is followed in Section-3 with a more detailed discussion of the hydroponic forage production greenhouse facility, support, and monitoring systems established and used in this project. In Section-4 we describe the forage production operations monitoring process used, and provide a preliminary performance assessment based on the limited data gathered and analyzed. Section-5 discusses forage nutrition assessment and presents results provided by our colleagues at New Mexico State University. Initial analysis and visualization of environmental data captured by the wireless sensor network is presented and discussed in Section-6. Conclusions and recommendations are given in Section-7. Selected reference material is provided in the appendices in Section-8.

Figure 1-4 Project Site at Livestock Border Crossing Facility in Santa Teresa, New Mexico. Upper left photo is view toward southeast showing the greenhouse site (in the foreground) prior to construction. The U.S.-Mexico border is a fence barely visible beyond the people in the photo. The city of Juarez in Chihuahua, Mexico, is beyond and to the left of the mountains seen in the background. The city of El Paso, Texas is further left of the mountains (out of the view of the photo).

Figure 1-5 Hydroponic forage greenhouse project system built in Santa Teresa, NM. Greenhouse is covered with plastic glazing material and shade-cloth (50% shading) to reduce interior light intensity and overheating. Structure on right is a surplus 20 x 8 x 8-foot double-insulated refrigeration transportainer with stainless steel interior and lock for secure on-site storage of seed, equipment, and other supplies.

1.5 References

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2 Hydroponic Forage Production – A Forage Factory

Hydroponic forage production involves a multi-step process for converting carbohydrate-filled grain seed into fresh forage consisting of a dense mat of mature sprouts that include root mass, seed residue, and green foliage. The resulting dry weight equivalent forage product is intended to provide a more balanced and nutritious mix of protein, carbohydrate, and mineral content for livestock feed than does the starting seed grain [1-5]. The seed, which can be any of a number of different types of grain, is first washed and disinfected by submerging and stirring in a dilute chlorine water bath. Any trash materials (empty seed coats, insects, etc.) that float to the top of the bath are skimmed off. After cleaning and rinsing, the seeds are then again submerged in water and allowed to soak for 4 hours, after which they are drained, covered, and allowed to sit overnight. The process of soaking and sitting overnight typically has a minimum duration of 12-hours. The process softens and loosens the seed coat, and initiates seed germination.

The damp germinating seeds are ready the following day for placement in trays for growing the forage. The seed is spread in an even layer several seeds thick over the bottom of shallow plastic trays that have been cleaned and disinfected prior to seeding. The seeded trays are then placed on racks within the greenhouse for growing. The trays are kept moist with a sprinkler irrigation system that turns on briefly at frequent intervals during the day. After 7-10 days of growth, the grain sprouts are typically 8-10 inches tall and ready for harvesting, post-processing, and feeding to livestock.

Following harvest, the trays are cleaned with soap and water and disinfected by rinsing in a dilute chlorine water bath, after which the seeding and growing process is repeated. This process is staged so that at any given time different ages of crop growth will exist within the greenhouse system. For crop maturation in 10 days, the process will be adjusted so that there will be 10 different stages of crop growth at any given time, and only the desired fraction (e.g., 1/10) of the total volume of crop in the greenhouse will be harvested daily. The operation is designed to run continuously 7-days per week with harvested forage output and newly seeded tray input taking place on a daily basis. Seed preparation occurs daily, resulting in germinating seed that will be ready for placing into trays the following day. The overall operation is essentially a forage factory.

The covered greenhouse structure moderates the environment for crop growth, protects against inclement weather, and reduces the evapo-transpiration losses that dominate the water consumption by open field forage crops. High light intensity is not required for this type of sprout growth, and it can also be done with some success in covered bins or shed-type structures. However, sufficient light is needed to increase photosynthesis and protein formation in the green foliage of the plants. The greenhouse system used in this project was designed to provide good growing environment, abundant light, and ease of access for operations. Figure 2-1 gives a summary of the steps in the forage production process. The following subsections describe each of these steps in more detail [2-3].

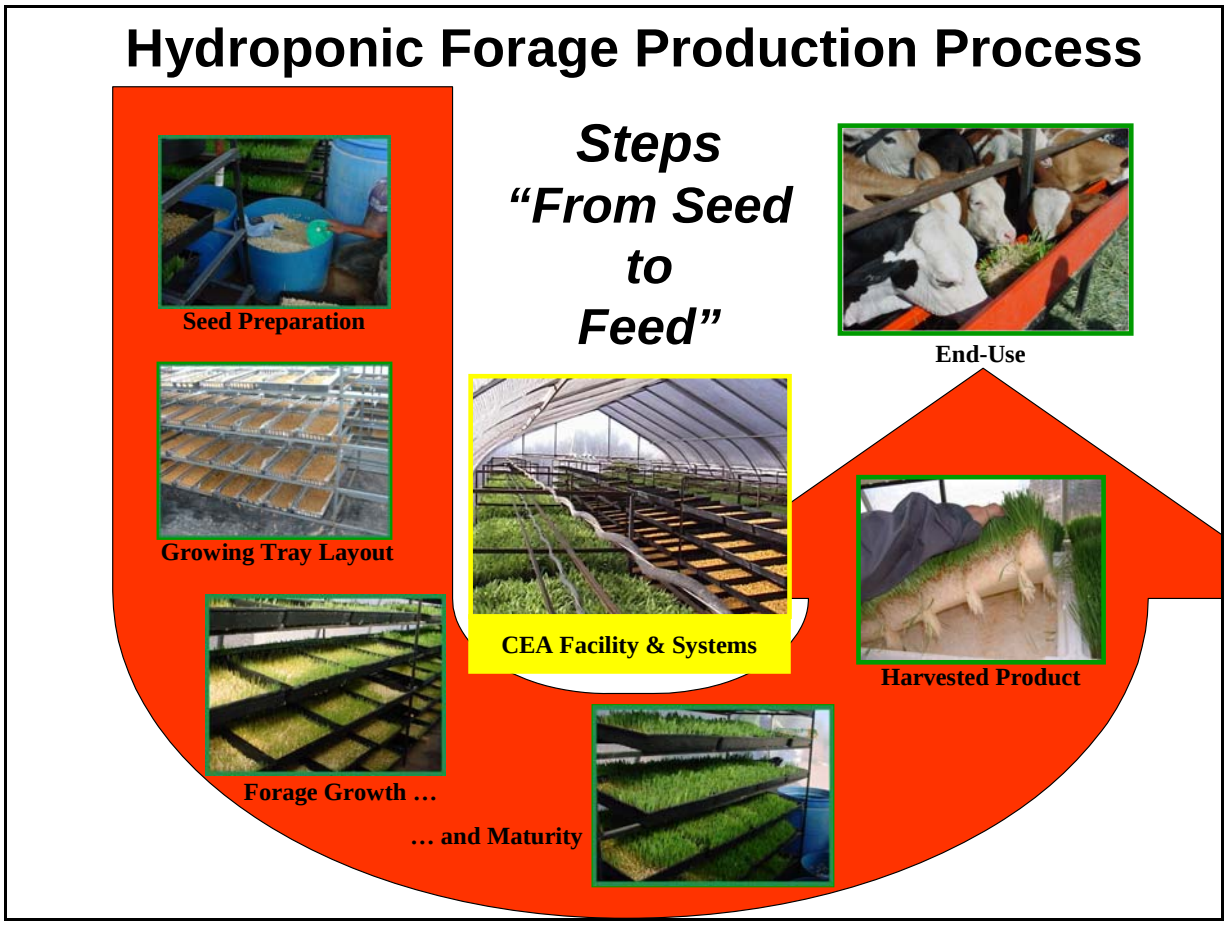


Figure 2-1.Hydroponic greenhouse forage production process overview.

2.1 Seed and Tray Preparation

The first step in the hydroponic forage production process is the combination of seed cleaning and soaking followed by tray cleaning, filling, and loading. These processes were all carried out on the concrete pad area outside the doors on the north end of the greenhouse. Six different types of seed (barley, corn, oats, sorghum, triticale, and wheat) were used in this project to compare the growing performance and nutrition content of the resulting forage product. The different seed types are shown in Figure 2-2. Each type of seed was weighed out separately and placed in individual plastic buckets with perforated sides and bottom. The perforations were made with a drill and sized to allow water to pass while retaining the seeds. The individual buckets of seed were then placed into a larger tank filled with water. The water level in the tank was set so that the seeds in the buckets would be submerged after the buckets were placed in the tank, as shown in Figure 2-3(a). The seed was washed with hand stirring for 10-15 minutes. Debris and other foreign material in the seed that floats to the surface of the water during this process is skimmed off and disposed of. Most of the remaining dirt and debris in the seed is removed by draining the wash water and rinsing lightly.

After the wash and rinse process, the seed, still in the plastic buckets sitting in the larger tank(s), was covered and allowed to soak for about 4-hours in a dilute chorine water

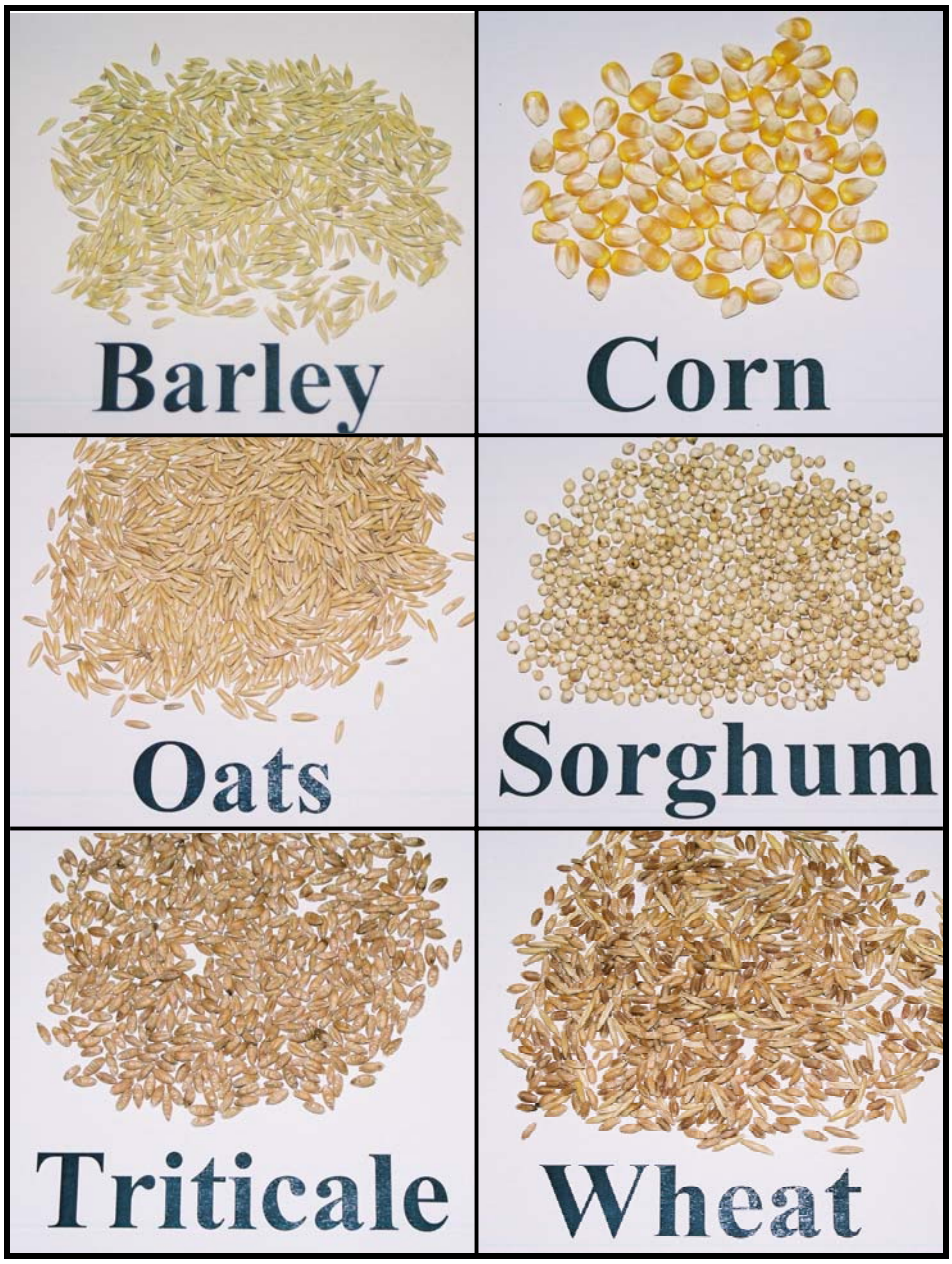


Figure 2-2 Seed types used in the project for growing hydroponic forage. For scale, the first (Capitalized) letter in each label is 7/8-inch (22.2-mm) tall.

solution containing about 0.01% sodium hypochlorite (chlorine bleach). After four hours of soaking, the water was allowed to slowly drain out of the large tank(s), and the covered buckets of damp seed were then allowed to sit for at least 12-hours (usually overnight). The process of seed washing and subsequent soaking is shown in Figure 2-3. The weak chlorine bleach solution was used to kill or reduce biological agents that could hinder plant growth or contaminate the forage product. Despite this step, the project was plagued by significant mold growth problems during the initial 3 weeks of operation from mid-August to early-September. This will be discussed further in Section 4. To create the desired density and fullness of the finished forage product, the growing

(a) **(b)**

Figure 2-3 (a) Washing seeds prior to soaking. **(b)** Covered soaking of seeds. The seeds were soaked in dilute chlorine water for 4 hours, then drained and left covered for 12 hours (overnight). Each plastic bucket contained different seed types.

trays used in this project each required approximately 1-kg, or a little over 2-pounds, of seed. The total amount of seed needed per day depends on the number of trays to be planted with each type of seed or mix of seed being used. The Chihuahua system used in this project can hold a total of nearly 1800 trays. For maximum capacity operation with a 10-day growth cycle, this requires processing enough seed for 180 trays per day. The project initially started operations at this maximum level with the six different seed types equally distributed among the 180 trays. This required about 75- pounds (enough for 30 trays) of each type of seed per day, with a combined total for all six seed types of about 450-pounds daily. As will be discussed later in Section 4, this varied somewhat and was later reduced to 3 seed types and a smaller volume of trays per day due to man-hour constraints for daily on-site operations.

2.2 Seed Germination, Tray Planting, and Racking

Forage growth begins with seed germination. The seed washing and soaking steps discussed earlier loosens and softens the seed coat and initiates the germination process. At the end of the 12-hour (or overnight) rest period, many of the softened seeds will have actually begun to sprout. At this point they are ready to be spread in the bottom of the growing trays, and the trays placed on the rack shelves in the greenhouse. Before seeding, the trays are cleaned by washing in soapy water and

(a) **(b)**

Figure 2-4 (a) Newly planted trays of germinating seed; (b) Rack of trays in various stages of forage growth.

rinsing in dilute chlorine bleach solution. The larger stock tanks are again used for this process. A thick layer (4-to-5 seeds deep, which completely covers the tray bottom) of damp germinating seed is spread evenly on the bottom of each tray. The trays are then stacked on a hand cart and transported through the doors into the greenhouse and along the appropriate aisle to the rack location where the trays are to be placed. Each of the four rows of rack in the greenhouse have seven layers of shelf for holding trays on each side of the rack. This is illustrated in Figure 3-3, and will be discussed further in Section 3. Trays of germinating seed are shown on rack shelves in Figure 2-4(a).

2.3 Irrigation and Forage Growth

The trays of germinating and growing seed sprouts, as shown in Figure 2-4(b), were watered periodically throughout the day by pressurized sprinkler lines running along the center line of each rack. Each level of shelving in the racks had its own sprinkler line to water the trays on that shelf. The water lines were activated periodically during daylight hours by a controller unit. The system would nominally begin watering the trays in the morning after the controller detected sunrise. Watering would continue throughout the day at intervals of typically 20-30 minutes, depending on humidity conditions within the greenhouse and/or the timing increment setting of the controller. At each watering, the lines would be pressurized through a solenoid valve, and the spray nozzles would turn on for a duration of about 20-seconds, depending on the setting of the controller. The watering would stop at sundown, and resume again the next morning. This process continued throughout the growing cycle of each tray of forage, with the goal of keeping each tray of seeds and sprouts sufficiently moist for healthy growth without over-watering. This ended up being difficult to do in practice with the existing system configuration, which will be discussed further in Section 3.3. A multi-day forage growth sequence is shown for corn in Figure 2-5(a), with racks of forage in different stages of growth shown in Figure 2-5(b).

(a) **(b)**

Figure 2-5 (a) Growth sequence of corn forage from day 2 (bottom) to day 10 (top); **(b)** Racks of grown (left) and growing (right and top) forage.

2.4 Forage Maturation and Harvesting

The last step in the forage production process is maturation and harvesting. The time needed for optimal forage grow-out or maturity typically ranges from eight to ten days, depending on the season, growing conditions, and the type of cultivar used. Each day, the trays that have reached maturity are removed and the forage harvested, as shown in Figure 2-6. The harvested forage can then be cut into smaller pieces and fed directly to livestock, or can be chopped and mixed with other feed and supplements to create a ration with desired or needed nutrition content balance.

(a) **(b)**

Figure 2-6 Forage harvesting: (a) Removal of tray from rack shelf; (b) Mature forage product removed from tray.

2.5 References

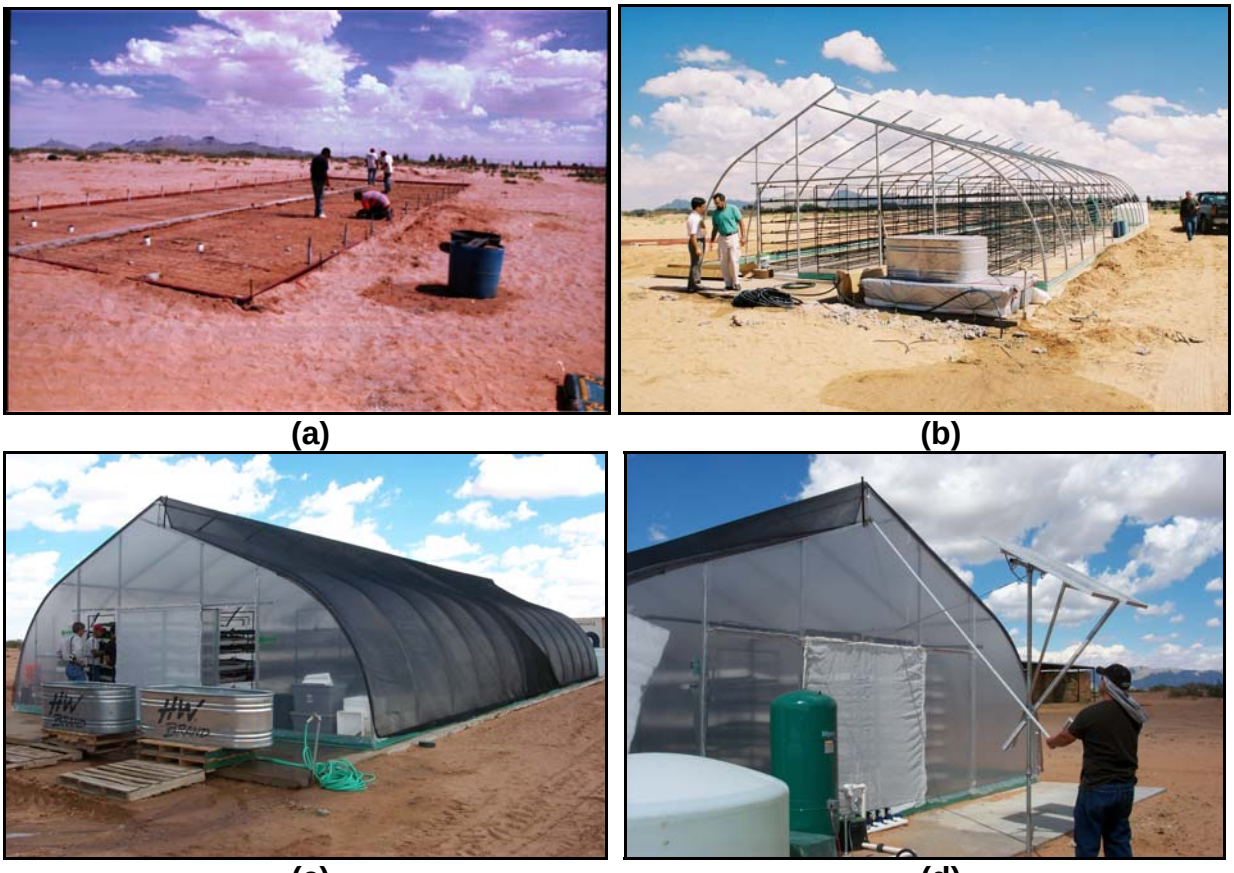
[1] United States Patent 6,578,319. Cole, Robert. Lloyd, Douglas. December 4, 2001.
[2] http://www.hydroponics.com.au/back_issues/issue70.html
[3] http://grazegreen.com/
[4] Pavel Rotar, “Hydroponic Techniques Sprout Healthy, Inexpensive Fodder”, ISAR: Initiative for Social Action and Renewal in Eurasia, [http://www.isar/isar/archive/ST/hydroponics47.html].
[5] Personal communications with Dr. Hector Leon Gallegos, Chihuahua, Mexico.

3 Project Forage Production Facility and Systems

The hydroponic greenhouse forage production system was built at the Livestock Border Crossing Facility in Santa Teresa, New Mexico. The facility is owned and operated by Union Ganadera Regional de Chihuahua, and is a set of livestock pens set up on each side of the U.S.-Mexico border to facilitate agricultural livestock trade between the two countries. Figure 1-4 shows the location of the site. The facility has a capacity for 24,000 head of cattle and operates to transfer livestock north and south. The forage greenhouse (Figure 1-5) was set up at the northeastern edge of the livestock pens.

3.1 Greenhouse Facility Structure and Cover

Greenhouse construction began in mid-July and was completed in early-August, 2004 by Aguirre Greenhouses of Chihuahua, Mexico. The structure, shown at various stages of completion in Figure 3-1, was 8 x 18 meters at the base and was placed on a four inch thick concrete slab, shown under construction in Figure 3-1(a). The framing



(a) **(b)**

(c) **(d)**

Figure 3-1 Sequence of greenhouse structure construction: (a) Preparing site for concrete pad; (b) Completion of pad, frame, and tray racks; (c) View of north end after application of plastic glazing and shade cloth showing access doors, seed preparation area, and water supply faucet; (d) View of south end showing manual adjustment of upper ridge air vent. Also seen are water system components, end wall air intake vent, and PV array.

trusses, shown in Figure 3-1(b), are 2” x 2” square steel pipe with 1/8-inch wall thickness bent to the proper dimensions. The cover is a standard polyethylene plastic material. An outer shade cloth layer consisting of black woven organic material was mounted over the top cover of the greenhouse. The shade cloth is designed to block roughly 50% of the incoming light. The ends of the greenhouse are not shaded. Two plastic-covered sliding doors for access to the interior of the greenhouse were built into the north end, as seen in Figure 3-1(c). A square vent opening approximately 2-m x 2-m and covered with porous fabric was built into the center of the south end of the plastic greenhouse cover, as seen in Figure 3-1(d). The cover offset along the top ridge of the greenhouse was equipped with a manually adjustable vent. The vent consists of a narrow rectangular opening at the ridge offset running the entire length of the greenhouse. The opening is covered by the porous shade screen fabric which allows air flow. A roll of polyethylene plastic running the entire length of the ridge vent can be adjusted up or down, as shown in Figure 3-1(d), to open or close the vent to air flow. The longitudinal axis of the greenhouse structure is aligned north-south.

3.2 Forage Growth Rack and Tray System

The forage was grown in plastic Styrofoam trays that were stacked on each side of metal racks having seven layers of shelves. The shelves were constructed from painted ¾ inch steel angle iron fastened together with welding and nuts and bolts. Four sets of racks run lengthwise in the greenhouse and are accessible from aisles on either side, as illustrated in Figure 3-3. The four racks provide a combined total of fifty-six shelves, each of which can hold thirty-two Styrofoam trays, giving a total greenhouse capacity of 1792 trays. Figure 3-2a shows an aisle running the length of the greenhouse with two racks of shelves on each side. The trays, shown in Figure 3-2b, were 0.4-m x 0.5-m in

(a) **(b)**

Figure 3-2 (a) Racks (made of angle iron) with 7-layers of shelves to support forage growing trays. **(b)** Styrofoam forage tray (0.4-m x 0.5-m) with bottom edge drain holes.

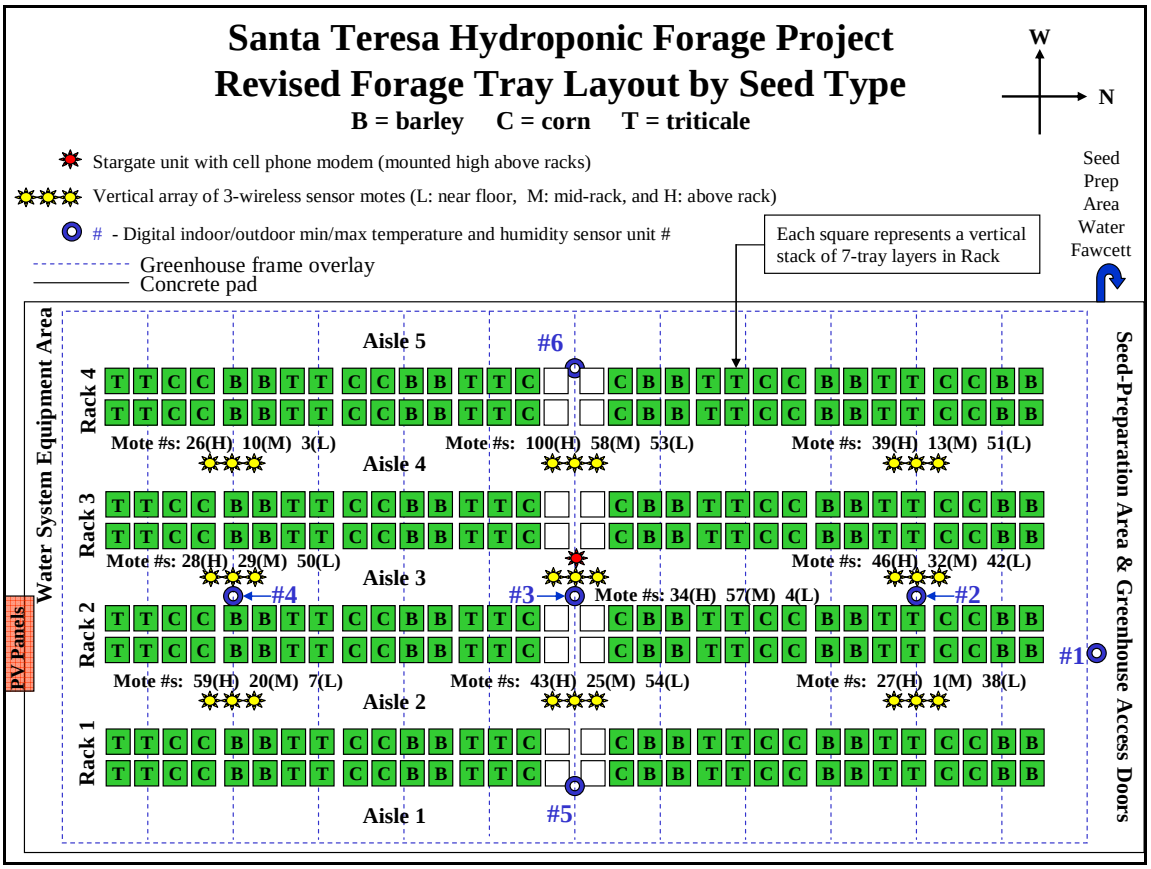


Figure 3-3 Simplified illustration of interior layout of greenhouse racks, trays, and environmental sensors. Ends of concrete pad exterior to the greenhouse not drawn to scale. Other systems (e.g., water, electrical, seed preparation) not shown.

size and equipped with drain holes along the bottom side edges to allow any excess irrigation water to drain off. Approximately 1-kg of dry seed (prior to washing and soaking) was used per tray during forage production operations. Each tray would then produce approximately 7-kg of harvested forage.

3.3 Water Supply and Irrigation System

A water system was needed to provide controlled irrigation for the growing forage and to provide water used for seed and tray preparation. The water system layout and components used for the project are shown in the diagram in Figure 3-4, and in the photographs in Figures 3-5 through 3-8. The water for the greenhouse system was provided by tapping into the water distribution system used to fill stock tanks in the cattle pens adjacent to the greenhouse site at the Livestock Border Crossing Facility. The stock tank water lines were pressurized from a pumped well and storage tank located on the other side of the livestock facility. The pressure at the far end of the distribution system where the greenhouse was located was very low, but was sufficient to deliver water to the 550 gallon storage tank at the south end of the greenhouse, and was initially thought to be sufficient for supplying a faucet used for seed and tray preparation at the north end of the greenhouse.

Following initial operation in August, problems arose that required changing the water supply system as shown in Figure 3-4b. The reason for these changes is discussed further in Section 4, but involved the need to pressurize the water for the seed/tray preparation faucet, and to provide the means to treat the incoming water by periodically adding swimming pool chemicals to the storage tank. The main elements of the system are shown in Figure 3-5. Figure 3-6 shows the 12-volt DC pumps used to charge the pressure tanks. Figure 3-7a shows the irrigation water flow meter and irrigation distribution lines leading into the greenhouse, while Figure 3-7b shows the water meter in the line supplying the faucet for the seed and tray preparation area.

Forage crop irrigation was contolled by a timer/controller unit shown in Figure 3-8a. The duration of the watering, and the timed interval between watering, could be adjusted with switch settings within the controller unit shown in Figure 3-8b. The controller contained a light sensor which turned the irrigation system off at night.

Each of the four racks of shelves for holding the forage trays were equipped with pressurized water lines running along each shelf layer. Spray nozzles for watering the forage trays were equally spaced along each line such that the water spray pattern would nominally cover all of the trays in the shelf associated with that line. All seven water lines associated with the seven shelf levels in a given rack were supplied simultaneously by a pressured supply line for that rack. The rack supply lines were each equipped with a solenoid valve controlled by the irrigation timer/controller unit. The controller could be set to rotate the irrigation among the four racks in sequence.

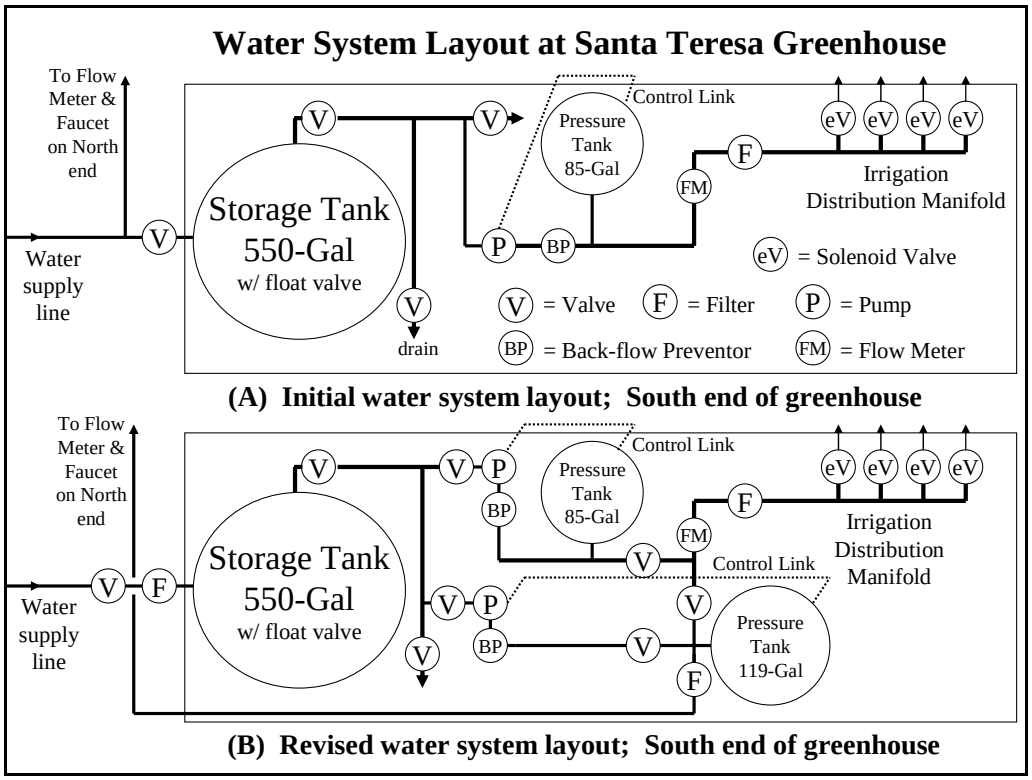
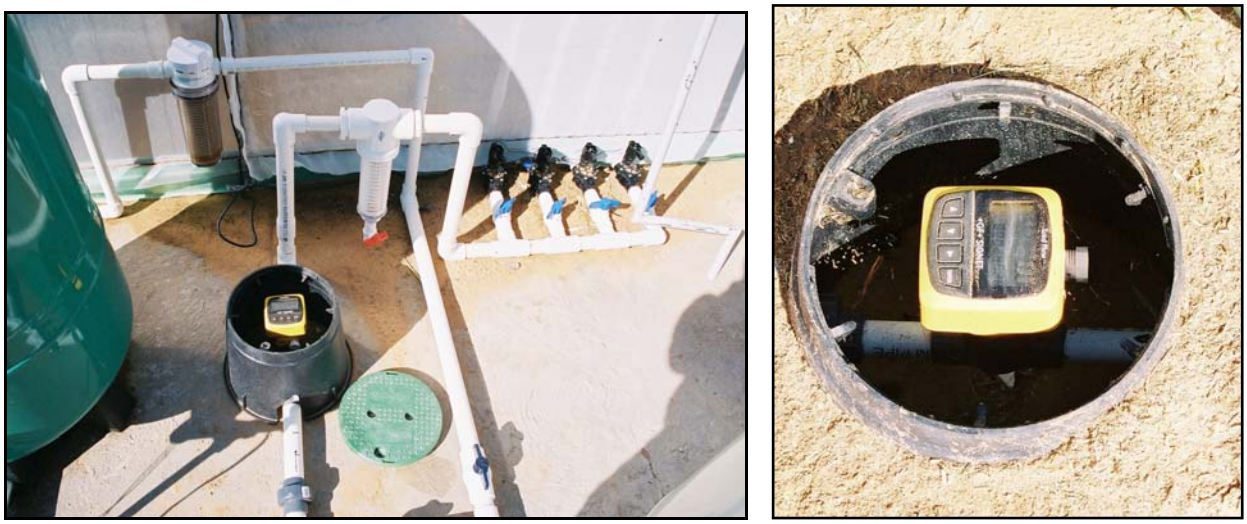


Figure 3-4 Water system: **(A)** before and **(B)** after addition of second pressure tank and pump.

Figure 3-5 Water system on south end of greenhouse facility. Edge of white 550-gallon storage tank is at far left. Pressure tank in middle supplies irrigation system. Pressure tank on right supplies a faucet on the north end of the facility for seed preparation, tray cleaning, and general use. Rectangular utility box houses the pumps. Round utility box houses the irrigation system flow meter.

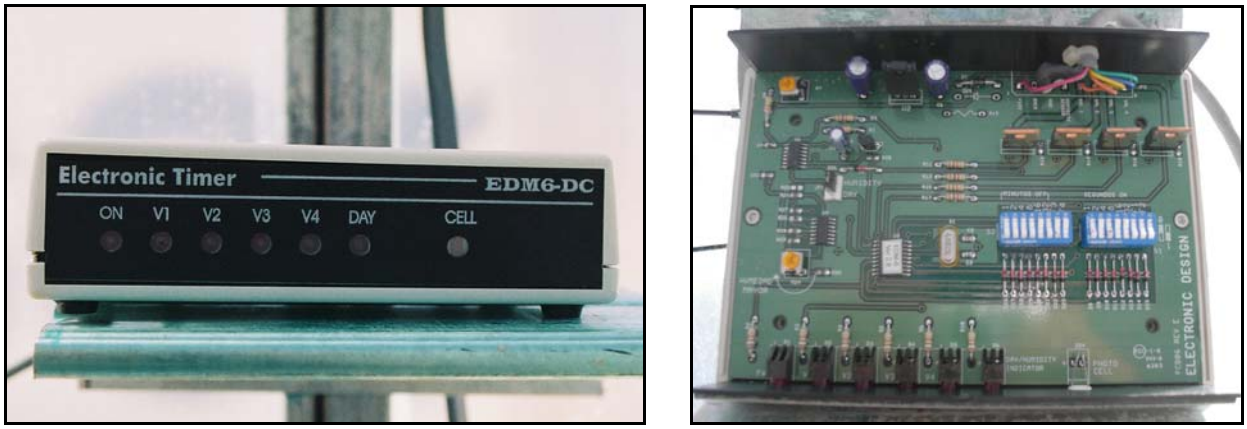
(a) **(b)**

Figure 3-6 **(a)** Pumps for transferring water from 550-gallon storage tank to pressure tanks **(b)** Close-up view of one of the 12-volt DC pumps (Flojet unit).



(a) **(b)**

Figure 3-7 (a) Irrigation system flow meter; (b) Flow meter in line to faucet used for seed preparation, tray cleaning, and other general purpose needs.



(a) **(b)**

Figure 3-8 (a) Irrigation controller unit. (b) Controller board showing switch blocks.

3.4 Environmental Monitoring System

Environmental monitoring and control is among the most important aspects of greenhouse operation. The environmental monitoring system employed in this initial effort is described in the remainder of this section. The purpose of controlled environment agriculture is to allow the plants to experience the optimal physical conditions to produce a maximum yield. The cost of this environmental control capability, however, is what makes CEA more expensive than traditional farming methods. The hydroponic forage greenhouse system implemented for this project has no active heating and cooling system, so is relatively modest and limited in performance capabilities and cost. CEA embodies complex and dynamic environmental, physical, and biophysical systems interactions. These can potentially be much more effectively and economically measured, understood, controlled, and optimized through the application and refinement of more densely distributed and networked SDACs that work in conjunction with appropriate greenhouse environmental control systems. Emerging

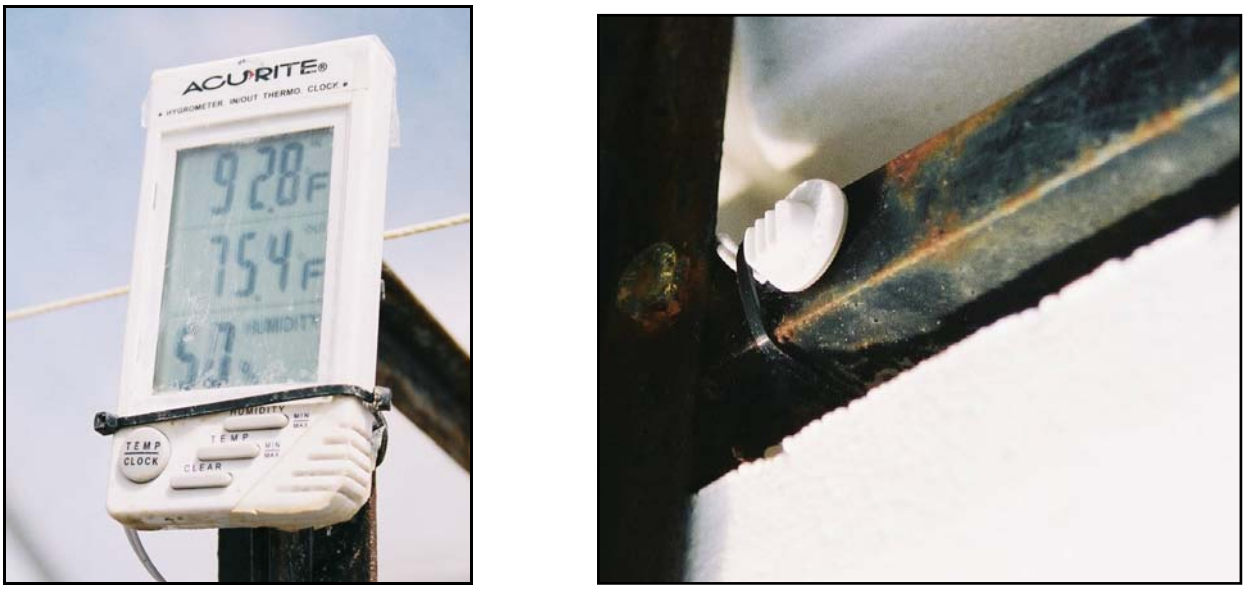
sensor systems can be expected to drop in cost and increase in performance over time. This will enable much more densely distributed and extensible monitoring, control, and adaptive optimization than would otherwise be possible. This project applied emerging commercially available systems technology to not only facilitate the experimental work, but to also gain experience to help guide further SDAC systems development work for this dual-use application area.

3.4.1 Min/Max Humidity and Temperature Sensors

The majority of the environmental data was taken by the wireless technology described below. A simple and inexpensive backup system was also used to capture daily extremes in temperature and humidity. Six Acurite sensors capable of recording daily minimum and maximum temperature and relative humidity were used. Each Acurite display/control unit, shown in Figure 3-9(a), has a temperature and humidity sensor built in. Each unit also has a remote sensor probe, shown in Figure 3-9(b), that can be located up to about 6-feet away from the display/control unit by a connecting signal wire. Five of these units (labeled #2 - #6) were mounted on the sides of the forage racks at the locations shown in Figure 3-3. The sixth unit (labeled #1) was mounted on the exterior of the north wall of the greenhouse between the doors. The exterior north wall location was shaded by the greenhouse from direct sun exposure throughout the day, and provided a measure of minimum and maximum outdoor ambient temperature and humidity conditions. The exterior Acurite system was mounted with the display/control unit placed near the top of the northeast door frame, and the remote probe mounted directly below a foot or so above the concrete floor. The display/control units inside the greenhouse were mounted near the top of the racks at a level slightly above the upper forage tray shelf height. Each external probe was attached to the rack directly below its corresponding display/control unit at the approximate level of the lowest forage tray shelf height. Each of the Acurite min/max units were placed at locations in the greenhouse so that they would be close to a hanging array of wireless sensor units in the adjacent aisle. The minimum and maximum data was recorded, and the units then reset, on a daily basis by the operations staff. This data is compared later in Section 6 with minimum and maximum values extracted from the time series data collected by the wireless sensor system.

3.4.2 Wirelessly-Networked Multi-Modal Sensor System

An array of 27 wirelessly networked sensor system “motes”, also referred to as network “nodes”, were deployed in the greenhouse to facilitate monitoring of environmental parameters, particularly temperature, humidity, and light intensity (IR and visible). The installation was planned to expand to 42 nodes, but time and resource constraints prevented mounting the additional units. The system is self-organizing and utilizes RF communications to provide data transfer and collection by a “mother-node” unit known as the “Stargate”. Key elements of the Crossbow mote and Stargate systems are illustrated in Figure 3-10 and Figure 3-11. The Stargate system provides local data aggregation and periodic uploading via cell phone link to a remote data collection computer maintained by project team members at Sandia’s California site. Collected data could then be processed and visualized off-line. Analysis and visualization of the environmental data collected by the system is discussed later in Section 6.



(a) (b)

Figure 3-9 (a) Min/Max temperature/humidity sensor display/control unit containing internal sensors. (b) External sensor unit connected to display unit by 6-ft of wire.

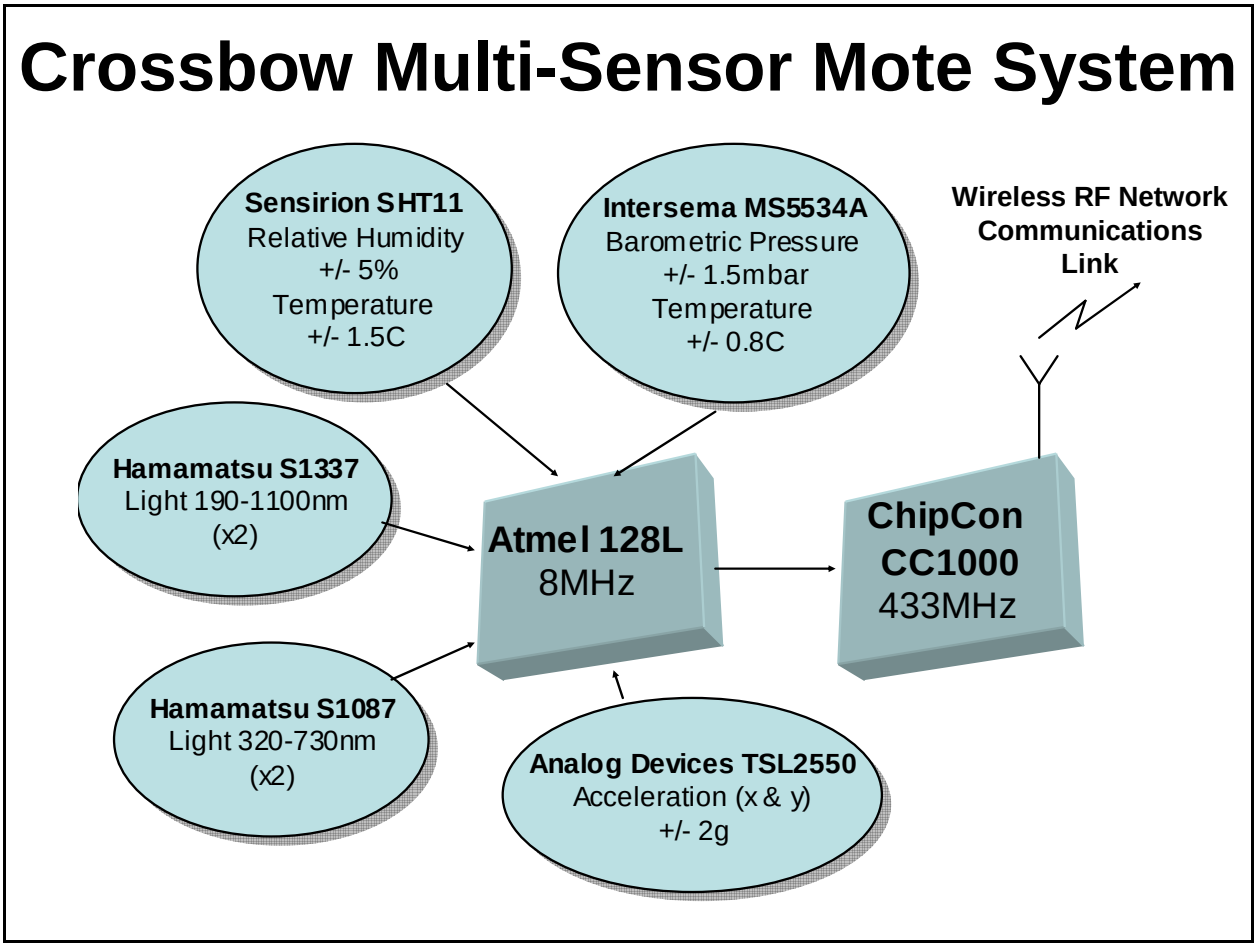


Figure 3-10 Sensor, Processor, and Communications Subsystems in Crossbow Motes.

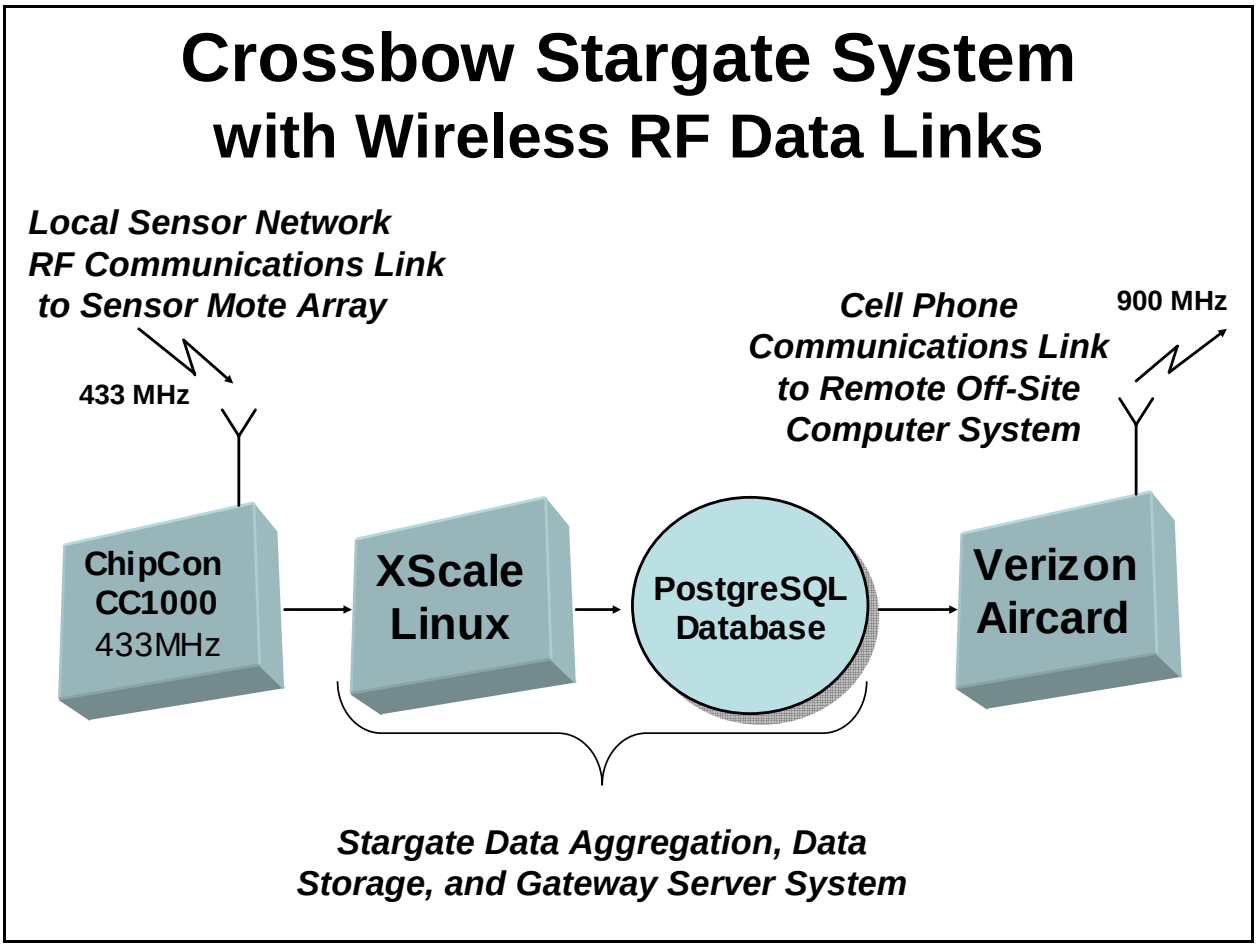


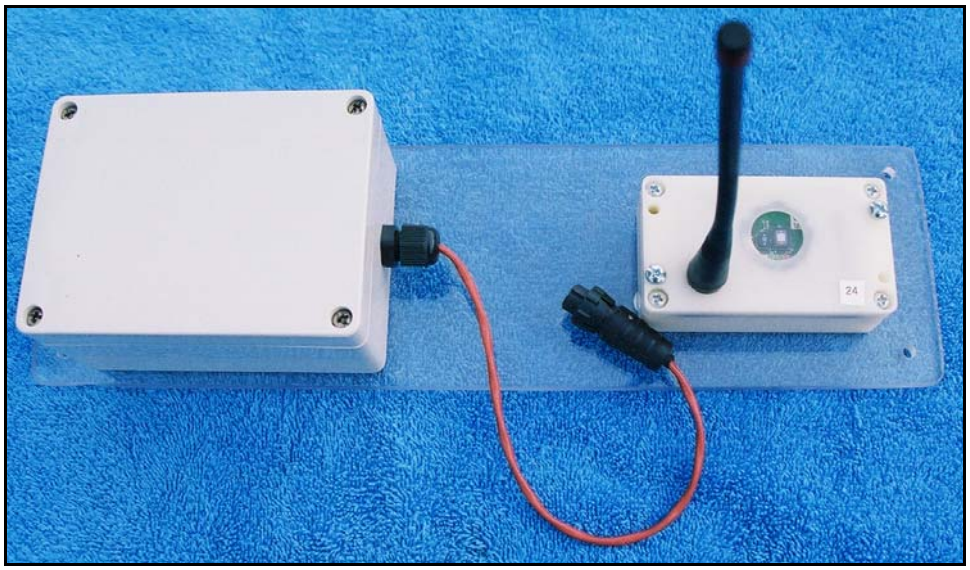
Figure 3-11 Crossbow Stargate system with local and remote RF communication links.

3.4.3 Wireless Sensor Motes

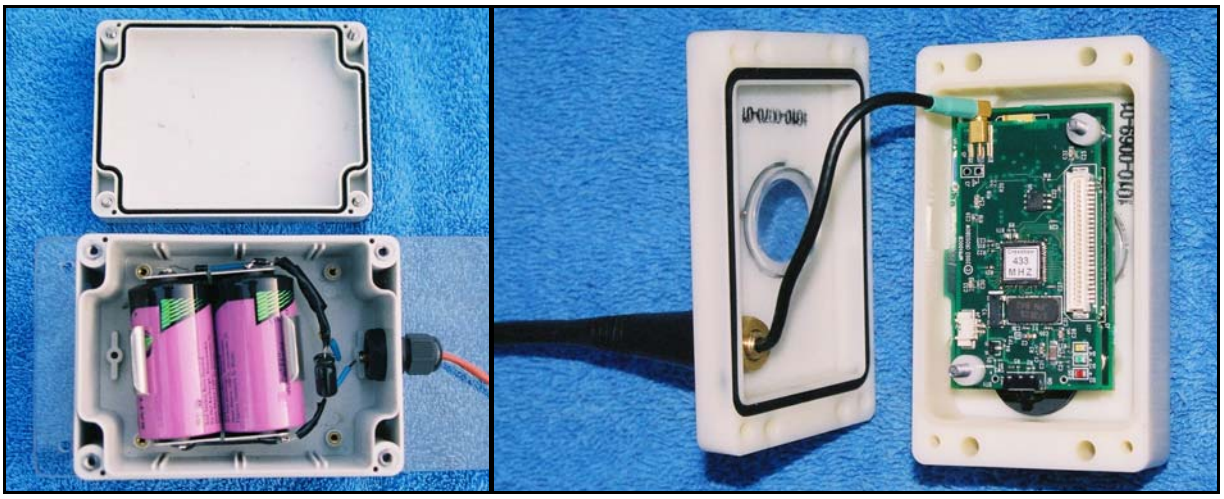
The system consists of an array of self-organizing sensor nodes implemented with multi-modal sensor motes available commercially from Crossbow Technologies. Each node contains a processor, a radio transmitter and receiver subsystem, battery, and sensor kit housed within an environmentally-sealed enclosure. A fully assembled wireless sensor node unit, consisting of the wireless sensor mote and battery box mounted on a lexan plate for deployment in the greenhouse, is shown in Figure 3-12(a). A closer view of the open battery box is shown in Figure 3-12(b). The heart of the node system consists of the *Mica2* "mote" from Crossbow Technologies that provides the following:

- 8MHz Atmel ATMega 128L microcontroller
- 4KB RAM,128KB program Flash ROM, 512KB data Flash ROM
- ChipCon CC1000 radio operating at 433MHz
- A 51-pin expansion connector for sensor interfacing

The system uses the MEP401 sensor board pair, also manufactured by Crossbow. The sensor boards mount above and below the main Mica2 mote board using the 51-pin



(a)



(b) **(c)**

Figure 3-12 (a) Wireless sensor mote with battery box on 4-in x 14-in Lexan mounting plate. **(b)** Open battery box (3.5-in x 4.75-in) showing 2 D-Cell lithium batteries. **(c)** Sensor mote with top cover opened and top sensor board removed to reveal main processor board with RF section.

expansion connector. The main Mica2 mote board is shown exposed (the upper sensor board has been removed) within the opened environmental case in Figure 3-12(c). The MEP401 boards provide the following sensors: internal and external temperature and humidity, ambient light (UV and visible, top and bottom), and barometric pressure. The key sensing, processing, and communications elements of each node are shown in Figure 3-10. Figure 3-13 shows an exploded view of the components that make up each sensor node. These components are housed in an environmental enclosure designed by Crossbow [Figure 3-12(c) and Figure 3-13]. The motes are powered by a custom battery enclosure made at Sandia which houses two 3V D-size lithium batteries shown in Figure 3-12(b). Both enclosures are mated via a weatherproof cable and

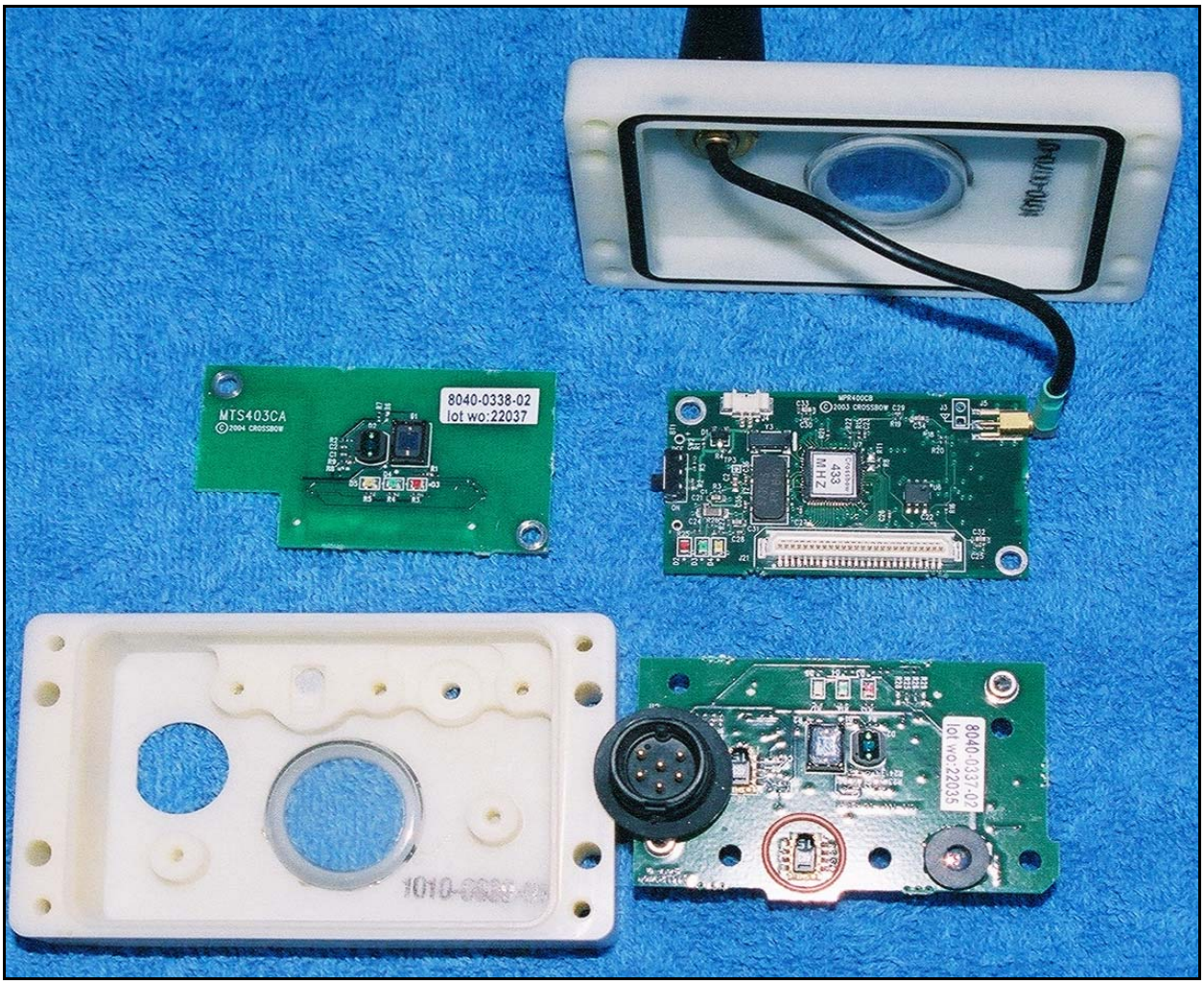


Figure 3-13 Sensor mote disassembled showing top and bottom sensor boards, center Mica2 processor board with RF section, and bottom case. Case is 2-inch x 3.5-inch. Windows in case provide access for light sensors and mote status LEDs.

attached to a lexan mounting plate shown in Figure 3-12(a). The mounted nodes are suspended from the overhead frame of the greenhouse using nylon lines with slip-bead stops to allow easy height adjustment shown in Figure 3-15(a). The motes were hung vertically in groups of three, with the low, middle, and upper motes adjusted to be at heights of 0.25-m, 1.15-m, and 2.1-m, respectively, above the floor. This is shown in Figure 3-16(a).

The 3-mote arrays were hung at three different locations along the three center aisles of the greenhouse, as shown schematically in Figure 3-3. To provide access to the aisles during forage production operations, each hanging array of motes was equipped with a line that could be used to temporarily raise and secure them safely out of the way above the aisle. Upon completion of work requiring aisle access, the motes would be lowered back into their normal monitoring position. See “Smart Dust Application Note” [1] for an excellent technical overview of the sensor hardware. The technical datasheet for the Mica2 [2] provides an overview of the mote itself.

3.4.4 Wireless Multi-modal Sensor Mote Capabilities

Each node is capable of sensing the environment, sending and receving packets of data over the radio, and performing algorithms on that data. The analog-to-digital converters (ADC) in the motes offer 10-bit resolution and each data packet can transport a payload of 29 bytes. Data is transmitted at 38.4k bit/s, manchester coded at 76.8k chip/s, and SECDED error correcting codes are employed to correct single bit errors. There are three LEDs which can be used to display status information for debugging and to ease trouble-shooting and status checking in deployment. The status LEDs are visible through the window in the top of the sensor mote enclosure. The nodes run the TinyOS operating system [3, 4] developed by U.C. Berkeley and a sensing application provided by Crossbow and modified by Sandia.

TinyOS is a small but powerful operating system designed around the NesC language [5]. NesC is an extension of the C language that adds language-level support for events, tasks, and modular code. When a programmer is writing an application for a TinyOS-compatible mote, he or she writes in NesC and “wires” the code components to components that are part of TinyOS. For instance, TinyOS provides a component for sending and receiving radio messages and the user can write code to perform arbitrary operations on those messages. The sensing application runs on each node and periodically samples the sensors and transmits a packet with the resulting readings to the Stargate (see Section 3.4.5). Additional details on the sensing application can be found in “Mote Software” in [1]. The motes are capable of implementing significantly complex routing algorithms, such as an ad-hoc “multi-hop” communication protocol. This can vastly extend the communication range because a mote need only be within range of one or more other motes and not necessarily the base station itself.

The sensing application mote software provided by Crossbow implements the following basic algorithm:

1. Wait 15 seconds
2. Read every sensor
3. Transmit a packet with all the readings.

The software can be configured to use multihop communication but we experienced technical difficulties with that software. Due to time constraints the decision was made to use single-hop communication, which is acceptable because of the limited geographic range of the nodes in this deployment. Sandia modified the sensing application to be:

1. Wait 15 seconds
2. Wake up from sleep mode
3. Set watchdog timer
4. Read every sensor
5. Clear watchdog timer
6. Transmit a packet with all the readings
7. Go into sleep mode.

Steps (2) (3) (5) and (7) were added to provide robustness to software failures and to extend the operational life of the nodes. If the watchdog timer is not cleared, then the mote will self-reset. Using a conservative estimate of 7mA average current draw, the motes should last for approximately 89 days. The LEDs are configured as follows:

- All LEDs nominally off.
- Red on → transmitting data packet.
- Green on → sensing environment.
- Green blink → blinks briefly every 2 sec to indicate operation.

3.4.5 Stargate System with Remote Cell Phone Link

The gateway for the sensor network is a Stargate single board computer, supplied by Crossbow Technologies, that also acts as a local data aggregation and storage unit for the network of sensor nodes. The Stargate, at its core, is a small PC running a 400MHz Intel XScale processor with 64MB of ram and 32MB of flash memory (Figure 3-14a). In addition to the Compact Flash and PCMCIA adapter slots, the board features headers which can accept Mica2 mote, I2C, JTAG and a daughter-card with Ethernet, Serial and USB ports. The small physical size of the unit, only 3.5" x 2.5" without expansion cards, and the low power consumption make it ideal for use as a remote gateway. As installed, the Stargate was powered with a DC-DC converter connected to the load distribution center of the solar power system (Figure 3-17) used to provide electrical power for the pumps and irrigation control system used in the greenhouse.

(a) **(b)**

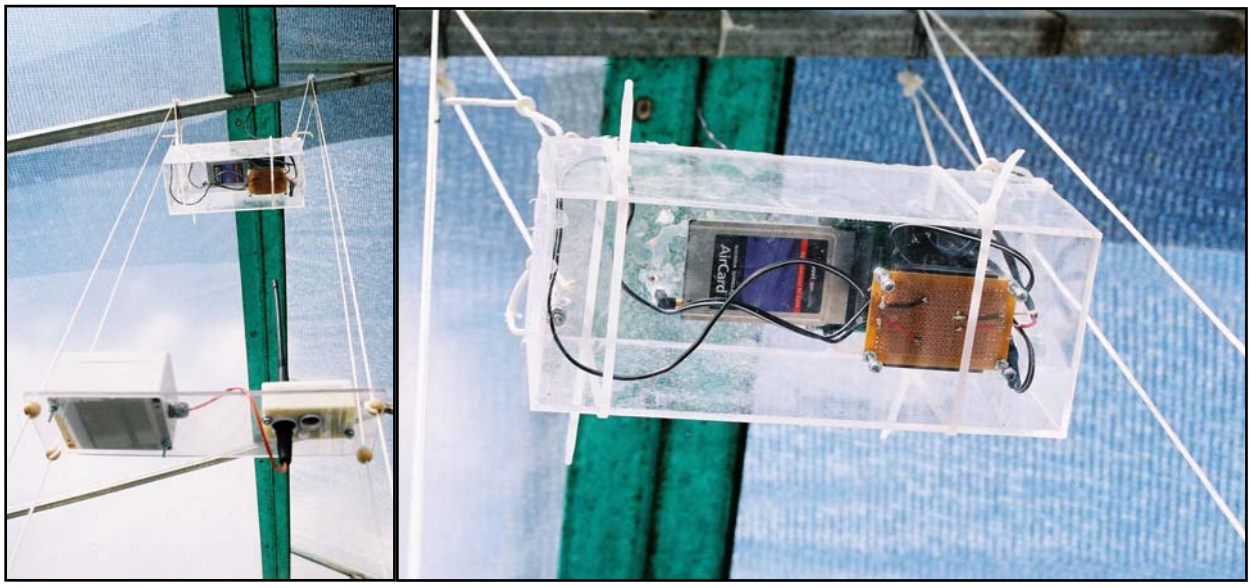
Figure 3-14 (a) Stargate system; **(b)** Cell phone modem that plugs into Stargate.

The Stargate runs an installation of GNU/Linux, a free and open-source operating system. As a result, extensive hardware and software resources are available without need for significant additional resources. Specifically, there is support available for a variety of wireless and wired modems, USB thumb drives, and other useful peripherals.

For our implementation, the Stargate served two main purposes: 1) data aggregator for the sensor nodes, and 2) remote gateway for uploading the collected data. For data aggregation, a Mica2 mote was attached to the 51-pin connector of the Stargate and

used to communicate with the remote sensor nodes. Software coded by Crossbow collected the data received from the sensor nodes via the attached mote. Once a data packet was received from a sensor node, it was parsed to retrieve the individual sensor readings, time-stamped, and then placed into a Postgres SQL database. The database was stored on a 128MB compact flash card. To upload the collected data back to SNL computers, a cellular wireless modem operating at 900-MHz – the Sierra Wireless AirCard 555 - was used to connect the Stargate to the Internet via Verizon cellular service (Figure 3-14b). The key wireless communications, processing, and data management elements of the Stargate system as implemented in this project are shown in Figure 3-11. Custom software was created by Sandia to dump data out of the Postgres SQL database in a usable format, and to clear data which has been successfully uploaded from the database. A script coded by Sandia and run every hour ran through the process of uploading the collected data. The process for the script was as follows:

1. do
2. connect to the Internet with wireless modem
3. while (connection has not yet been established)
4. archive log files
5. dump collected data from database and archive
6. do
7. upload log files and collected data to Sandia server via SSH
8. while (uploads were not successful)
9. remove uploaded data from database
10. remove uploaded log data
11. disconnect from the Internet



(a) **(b)**

Figure 3-15 (a) Stargate system mounted in plastic enclosure near top of greenhouse. A wirelessly networked sensor unit is shown hanging below. **(b)** Closer view of suspended Stargate system with cell phone modem card.

(a) **(b)**

Figure 3-16 **(a)** Wirelessly-networked sensor mote units hung in aisles between racks; **(b)** Hanging array of sensor motes pulled up to allow aisle access during operations.

For the data dump process, it is not feasible to stop data collection from the sensors. As a result, a date and time bound are used to determine the data to be uploaded. The starting bound is the oldest data reading in the database, while the ending bound is set as the time at which the upload script was started. Any data collected during the dump process will be uploaded during the next connection.

To ensure the security and privacy of the data, encryption was used for data transmission and a hash algorithm was used to verify the data received at the Sandia server. SSH, a secure shell tool, provided the ability to connect to a Sandia server securely over public network connections by encrypting the connection. A cryptographic public/private key pair was generated for the purpose of automated authentication. Once the data was uploaded, a cryptographic hash algorithm – MD5 – was used to verify that the data had arrived at the server intact and unaltered. The combined Stargate with cell phone modem mounted in the greenhouse is shown in Figure 3-15.

3.5 Electrical Power System

The power used in the hydroponic forage greenhouse was obtained from two 85 watt photovoltaic panels configured in parallel, shown in Figure 3-17 and Figure 3-18(b). The DC electricity produce by these modules was connected via a charge controller, seen in Figure 3-18(a), to a bank of two 100 amp-hour lead-acid batteries connected in parallel, and to the electrical load distribution center equipped with ciricuit breakers. The overall power system with loads is illustrated in Figure 3-17. The power load demands were from the two water pumps, the irrigation system controller, and the Stargate unit that formed the gateway hub for the wirelessly networked sensor system. The system performed well during the project, with the exception of one or two prolonged periods of cloudy weather during which the pumping load required to keep the irrigation system operational consumed more energy than was being provided by the solar panels. This resulted in the temporary shut-down of the irrigation system until sufficient battery recharge could occur.

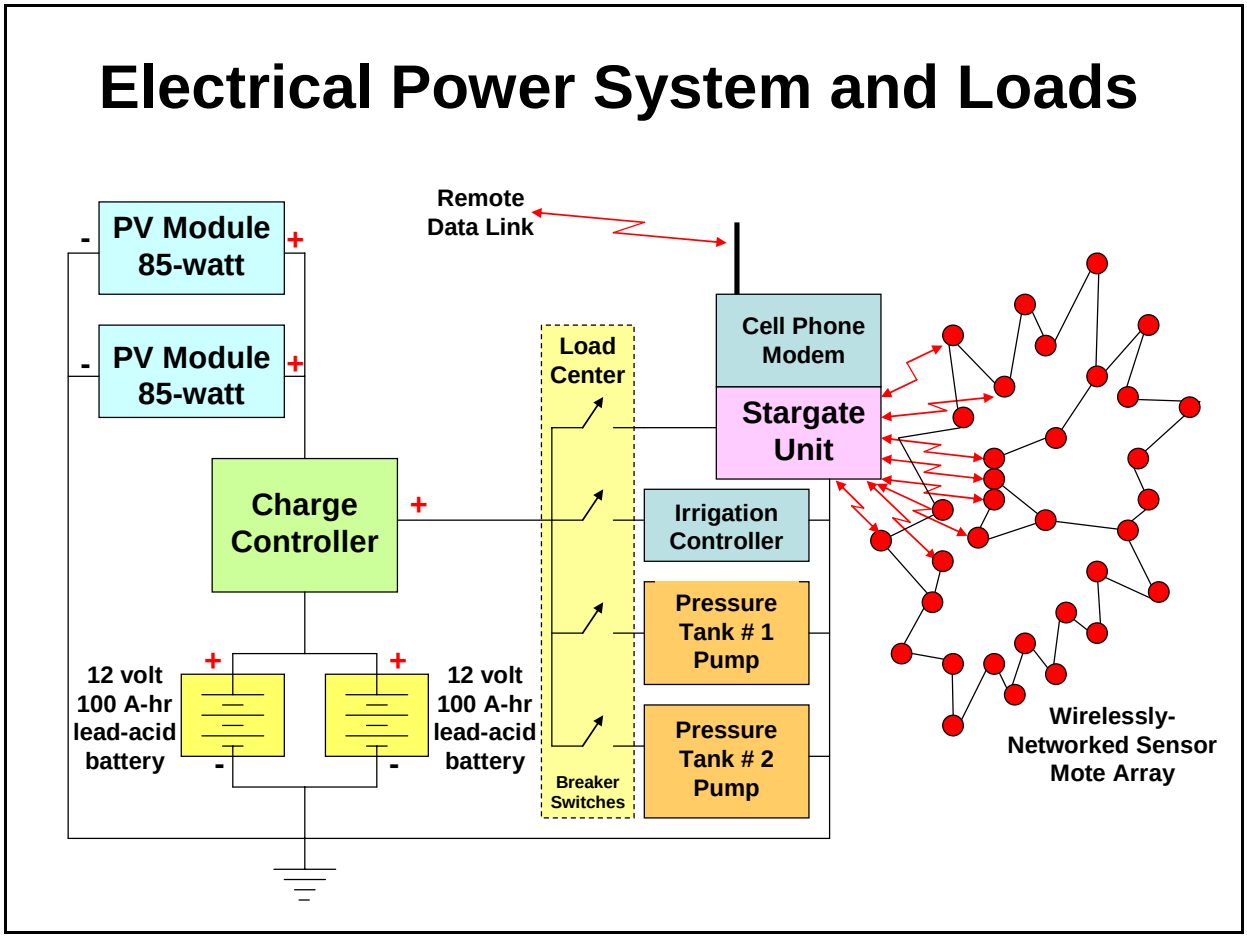


Figure 3-17 Block diagram of the greenhouse power system and loads.

(a) **(b)**

Figure 3-18 (a) Charge controller unit; (b) Photovoltaic array (two 85-watt modules) and mounting structure.

3.6 Seed and Supplies Storage

Seed and other equipment and supplies needed for the project were stored in a portable shed that was locked nightly (Figure 1-5). The storage shed, located just a few yards south of the greenhouse structure, consisted of a surplus 20 x 8 x 8-foot double-insulated refrigeration transportainer with stainless steel interior and locking mechanism.

3.7 References

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4 Forage Production Operations Monitoring and Preliminary Performance Assessment

Daily on-site forage production and monitoring operations were conducted with the support of four student interns from the University of Texas at El Paso (UTEP). The interns visited the site daily (with a few exceptions), usually in teams of two, for a period of from 3-to-6 hours per visit, depending on schedule and work-load. A log sheet was created to record daily operations and capture information needed to monitor operational performance of the forage production system. The log sheet, shown in Section 8.1 Appendix A, was designed to be filled out by the interns during their daily on-site operations. Besides following procedural steps like locking the storage unit and closing the water meter covers, the log sheets provided for the recording of data from the manually-read min/max temperature and humidity sensors and the water meters. Quantities and type of seed and other supplies used, the number of trays seeded, and the amount of forage harvested each day were also to be recorded, along with any problems or observations worthy of note.

The late-start LDRD funded portion of this project had a relatively short time window of only a few weeks during August-September 2004 to bring the newly constructed hydroponic forage greenhouse system into operation, work out operational problems, install and debug the environmental monitoring systems, generate as much forage and operational data as possible, and perform nutritional content analysis on forage samples. Additional modest funding support from other sources (NM Small Business Assistance bundled project and Sandia Center 6100 discretionary funding) fortunately allowed for a limited amount of operational work to continue into 1QFY05, which was necessary to collect and process environmental data from the debugged wirelessly-networked sensor system, gather additional water-use data, and provide demonstration of operations for several interested visitors from agricultural and educational organizations in New Mexico.

Student employment restrictions limited each intern to a maximum number of work hours per week, which required rotating the on-site visit schedule among the interns, with occasional support and oversight visits by Sandia staff from Las Cruces and Albuquerque. The intern work hour restrictions, short-duration nature of the project, and challenges associated with spinning up, debugging, and maintaining research operations at a relatively remote site ended up putting constraints on project scope and results that could be achieved during this initial project effort. For that reason, the results of this section, and the project overall, are considered somewhat preliminary.

The remainder of this section briefly describes the gathering and analysis of operational data. We discuss preliminary performance assessment results and several operational issues and problems encountered along the way.

4.1 Operational Performance Data and Assessment

Operational spin-up of the project began immediately following completion of the facility construction phase in late July. Forage production operations were initiated at the beginning of August following initial checkout of greenhouse systems and delivery of seed and other supplies. Daily operation of the greenhouse varied considerably through the end of FY04 and into early-FY05 due to the need for numerous system adjustments (particularly with the spray irrigation), modifications in the growing program, varying environmental conditions, and several problems that had to be addressed. Soon after operations began in August, a severe fly and mold infestation problem arose in the greenhouse. The source of the problem was not conclusively determined, but contributing factors were the close proximity of cattle and flies from the nearby pens, the hot August weather conditions, and persistent problems with the spray irrigation system that caused excessive wetting of the greenhouse floor and pooling of water conducive to attraction of flies and associated contamination within the greenhouse. The mold problem was assessed by experts at New Mexico State University (refer to report in Section 8.2 Appendix B), with the recommendation to maintain clean conditions and apply disinfection treatment where possible.

The raw water supply initially used to prepare the seed and irrigate the forage was also found to have high pH (7.8) and fecal coliform contamination. The fecal contamination was probably from lack of back-flow-prevention valves on the watering troughs in the adjacent cattle pens, which could have allowed contamination to get into the supply line feeding the greenhouse water storage tank. In addition to the mold and water quality problems, the water pressure available from the main supply line was found to be too low for efficient tray cleaning and seed preparation operations. Furthermore, the low water flow resulting from the low pressure was below the threshold for accurate measurement by the flow meter in the line going to the faucet in the seed/tray preparation area at the north end of the greenhouse. To address all of these issues simultaneously, greenhouse operations were shut down for three weeks beginning in late August to allow for systems reconfiguration, clean-up, and revision of operations.

The water system was reconfigured, as shown in Figure 3-4, by adding a second pump and pressure tank, shown in Figure 3-5, for supplying pressurized water to the faucet near the seed and tray preparation area. In addition, the water intake side of the system was reconfigured so that the new pressure tank and the original irrigation system pressure tank were both supplied from the 550-gallon water storage tank. A filter was also added to the input supply line side of the storage tank to trap solid organic material and other particles occasionally found in the supply water. From this point on, water in the storage tank was tested daily and treated with swimming pool chemicals (dry acid to correct pH, and chlorine to kill pathogens). These changes provided for the delivery of treated and pressurized water for both irrigation and seed/tray preparation. The shut down also allowed time to clean trays, install the wirelessly-networked sensor system, and add two electrical load center control breakers needed for the second pump and the Stargate unit with the remote data link. Debugging of the sensor mote array, Stargate, and remote cell phone data link was also initiated during the shutdown period and continued through the end of September.

Forage production operations resumed in the third week of September and ran through mid-November at a reduced level. Seed varieties used were reduced from six to three, and the number of trays processed daily were reduced to make the on-site labor requirements more manageable. On-site forage production operations for the project were finally shut down in November.

Figure 4-1 summarizes water use during the period from September 20 – November 4. Water use was based on daily, or nearly daily, recordings of water meter readings for the irrigation system and the seed/tray preparation supply faucet. The water use measurements are the differences of the water meter readings between log sheet data entries (in the places where there is more than a day gap between data entries the measurement is evenly distributed between the days. The water use during this period averaged about 300 gal/day for irrigation and about 250 gal/day for seed and tray preparation, for a total use of about 550 gal/day. Peak use excursions approaching or exceeding 800 gal/day are seen in a few cases. The extreme peak in water use seen during the period of Oct 27-31 was due to an irrigation controller problem that caused the irrigation system to cycle on much more frequently than it should have. Once detected and diagnosed, the problem was corrected and the water use dropped significantly as shown. A key observation is that nearly as much water was consumed, on average, doing seed and tray preparation, as was consumed for irrigation.

During this period, the number of trays being used for forage production was reduced down from the maximum system capacity in order to reduce the labor and on-site time required for daily operations. Instead of working with four growing racks with seven active shelves per rack, the operation was reduced to a variation of between two and three growing racks with only four growing shelves (and irrigation lines) active per rack. Control valves were spliced into the irrigation lines at the head of each rack to allow unused lines to be turned off. Rack #1 on the east side of the greenhouse was turned off completely and used for tray storage, while Racks #2-#4 were variously used for forage growth. On average during the period of water use observations in Figure 4-1, the forage production potential was approximately 70 trays per day. The actual "realized" forage production was often less than this due to operational constraints on the number of trays that could be handled daily with the time available, however the irrigation water was still being dispersed to trays along the active rack shelves whether forage was growing in those trays or not. This was an unfortunate limitation of the project system which did not allow irrigation system control of portions of a shelf line. The line along the entire length of the rack was either entirely on or entire off, which made partial operations difficult to do efficiently.

Measurements made of harvested forage over the course of project operations showed average harvested tray weight (lbs) as a function of seed type to be:

Barley	*15.6 lbs/tray*	*Corn*	*11.0 lbs/tray*
Oats	*15.6 lbs/tray*	*Sorghum*	*14.5 lbs/tray*
Triticale	*13.4 lbs/tray*	*Wheat*	*16.5 lbs/tray*

Average for all six seed types: 14.4 lbs/tray

Average for Barley, Oats, and Triticale: 14.9 lbs/tray

The average weight of forage produced per tray for all seed types was about 14.4 lbs, and was closer to 15 lbs for the three seed types used during the late-September to early-November period (barley, oats, triticale). At an average production potential of 70 trays per day at 15 lbs per tray, this yields an average of about 1050 lbs of forage harvest per day corresponding to the average of the daily water use shown in Figure 4.1. This equates to about 570 gal of water used per ton of fresh hydroponic forage produced, or about 4.3 gallons of water per tray produced. This is much higher water use than expected or required, and can be greatly improved upon by addressing the persistent problems encountered with the spray irrigation system configuration and its performance. The water use efficiency is worse if we factor in the water used for seed and tray preparation. In that case, the use becomes about 1048 gal of water per ton of fresh forage produced, or about 7.8 gallons per tray of forage produced. We believe that improvements can be made here also.

For comparison, open field alfalfa production in New Mexico averages about 5.5-tons (baled product) per year per acre with an average annual water consumption estimated to be about 3 acre-feet per acre per year. Assuming 3 acre-feet of water per year per acre, this equates to nearly 196,000 gal of water used per ton of baled alfalfa produced. Baled alfalfa has less water content than the fresh hydroponic forage, so if we calculate dry weight equivalents assuming 15% moisture content for baled alfalfa and 90% moisture content for hydroponic forage, we have the following estimates:

Water required to produce 1-ton dry weight equivalent open field alfalfa: **230,000 gal**.

Water required to produce 1-ton dry weight equivalent hydroponic forage: **10,480 gal**.

This assumes the worst case estimate above of 1048 gal of water used per ton of hydroponic forage. Despite the higher than expected water use results from this initial project, this still shows a factor of 22 improvment in water use efficiency over open field alfalfa production. Stated another way, this project produced hydroponic forage using **4.5%** of the water required to produce the same dry weight equivalent amount of alfalfa grown using traditional open field practices.

The mass of seed used in the planting step was about 2.1 lbs per tray for each type of seed. Hence, the mass increase during the forage maturation process ranged from a factor of 5.3 to 7.8, most of which represents water content (refer to forage nutrition analysis in Section 5). Since most of this is water added to the growing plant, minimizing the quantity of water used depends on achieving efficient delivery and management of only the amount of water needed by the plants. This project achieved less-than-optimum water saving performance primarily due to inefficiencies associated with the spray irrigation system adjustment and control.

In terms of labor, the daily man-hours required for conducing monitored operations varied from three to ten, and averaged seven throughout the experiment. The expected value of four man-hours per day was found to be a significant under-estimate, primarily because of the additional activities required by the workers due to the research

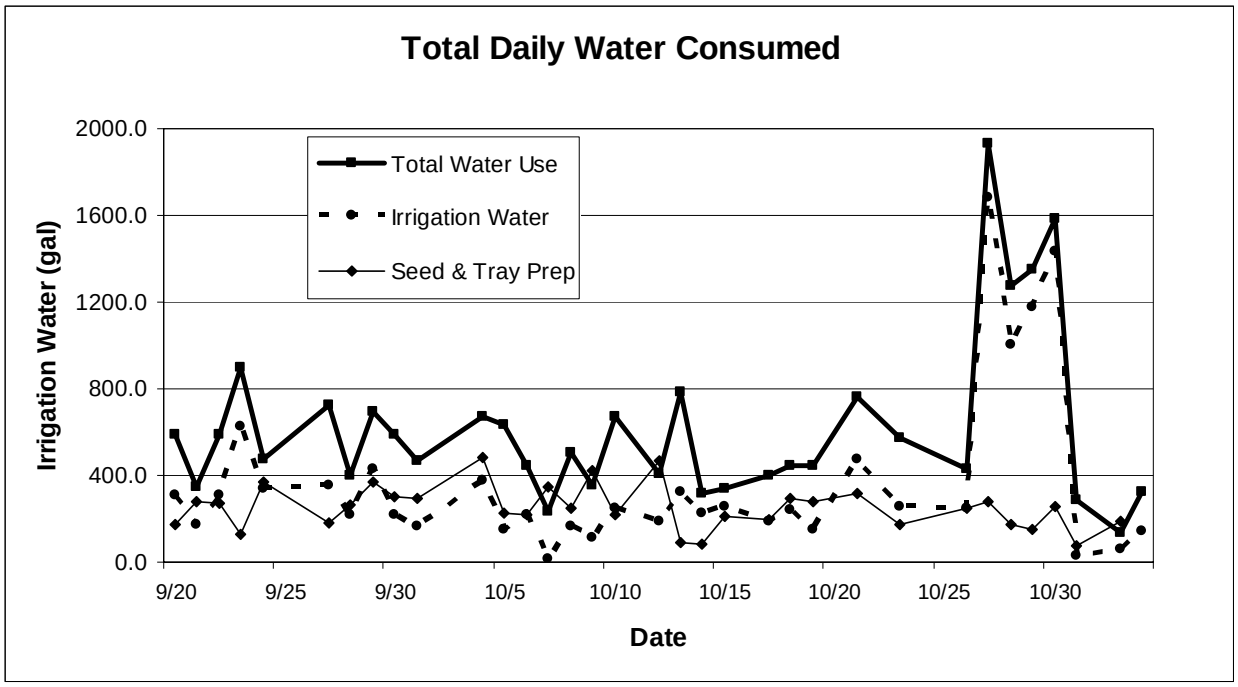

Figure 4-1. Daily water consumption from 09/20/04 to 11/04/04.

nature of this project. Such activities included filling out the daily reports, moving the suspended motes and using from three to six different types of seed. Despite the added time required for these research activities, the fact remains that the forage production process itself was very time-consuming and labor-intensive as practiced in this project. Effort is needed to better streamline the process and reduce both labor and water required in the preparation, growing, and harvesting steps.

Figures 4-2 through 4-5 represent the minimum and maximum temperatures recorded by the five min/max sensor units located at different locations and height levels inside the greenhouse and the two (upper and lower sensors) associated with the unit located on the outside the greenhouse. Each line on these graphs represents a different sensor location. The minimum temperature data shows relatively uniform agreement except for the extreme spikes in a few of the recorded readings. This is reasonable, given that the minimum temperatures will occur in the early morning hours following the long night period when temperatures throughout the greenhouse can be expected to reach fairly uniform equilibrium.

The spikes are likely due to recording error or failure of the operator to properly reset the unit for the next sequence of min/max readings (i.e., the spikes could represent maximum readings from the day before which are still present because the unit was not reset to take new readings). On the other hand, the maximum temperature data shows significant variation with location, with more variation at the higher (upper shelf) level than at the lower shelf level. This demonstrates that the environment in the greenhouse is inhomogeneous in both space and time during the day, which is also shown by the time-series environmental data presented and discussed later in Section 6. Figures 4-6 and 4-7 show the minimum and maximum relative humidity recorded at the higher

(upper self level) min/max sensor locations. The wide variability in both location and time (days when recordings were logged) suggests significant non-uniformity in the humidity conditions in both space and time, which is a reasonable expectation. This non-uniformity in humidity is likely exacerbated by the relatively crude spray irrigation system used in this project which lacks the level of spatial control and uniformity desired.

Figure 4-8 represents the daily averages of minimum and maximum temperature and humidity for the upper (interior) and lower (exterior) sensor readings averaged over all six of the min/max unit locations. Each data point on this graph represents an overall average of the minimum and maximum environmental conditions in the greenhouse. Interesting observations from the data in Figure 4-8 include that the difference between minimum top and bottom shelf temperatures over the period monitored was about 2.2°F, while the difference between maximum top and bottom shelf temperatures was about 11.1°F.

The average of the average minimum and maximum humidity data shown in the figure ranges from about 35% to about 75% over the period of observation, with peak maximum humidity reaching 100% and minimum average dropping as low as 10%. The correlation of these ranges in variation of environmental conditions with crop growth is an area of interest that we did not have the time or resources to address in this project, but hope to pursue in the future.

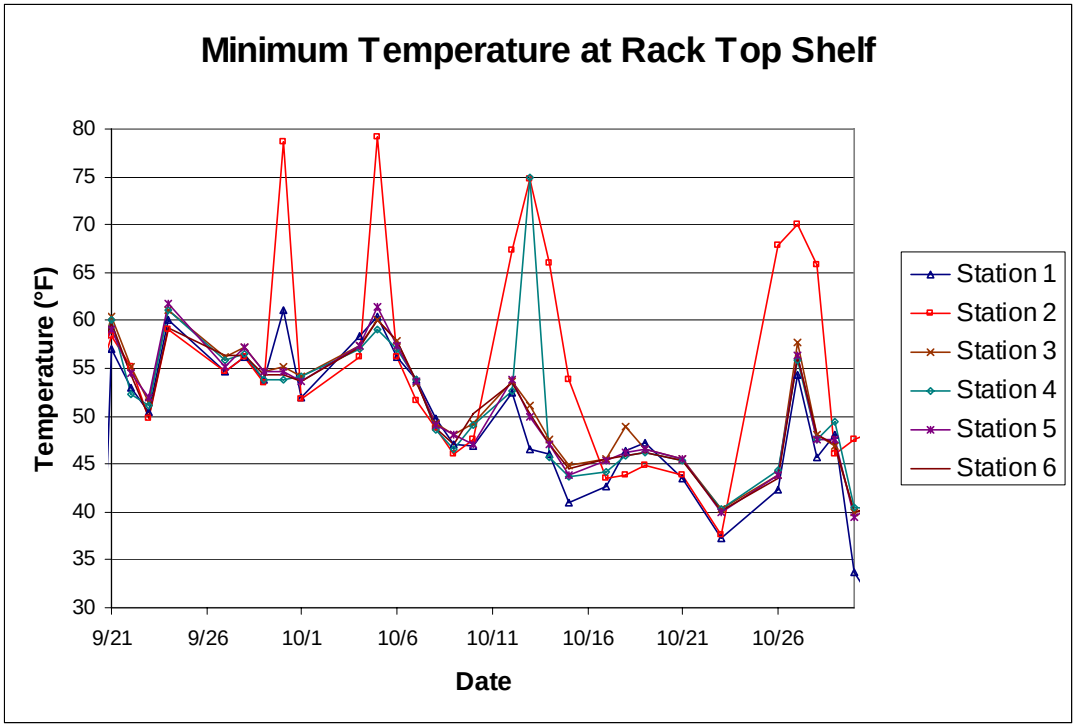

Figure 4-2. Minimum temperatures recorded near the rack top shelf locations of the min/max sensor units from 9/21/04-10/31/04.

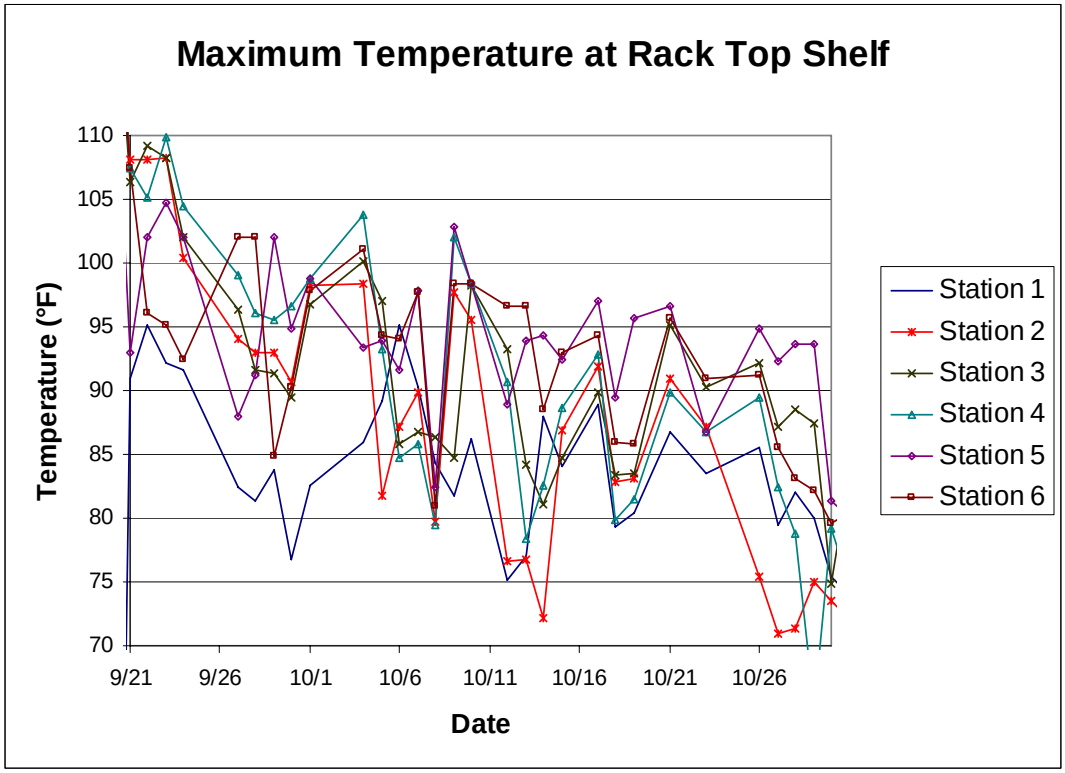

Figure 4-3. Maximum temperatures recorded near the rack top shelf locations of the min/max sensor units from 9/21/04-10/31/04.

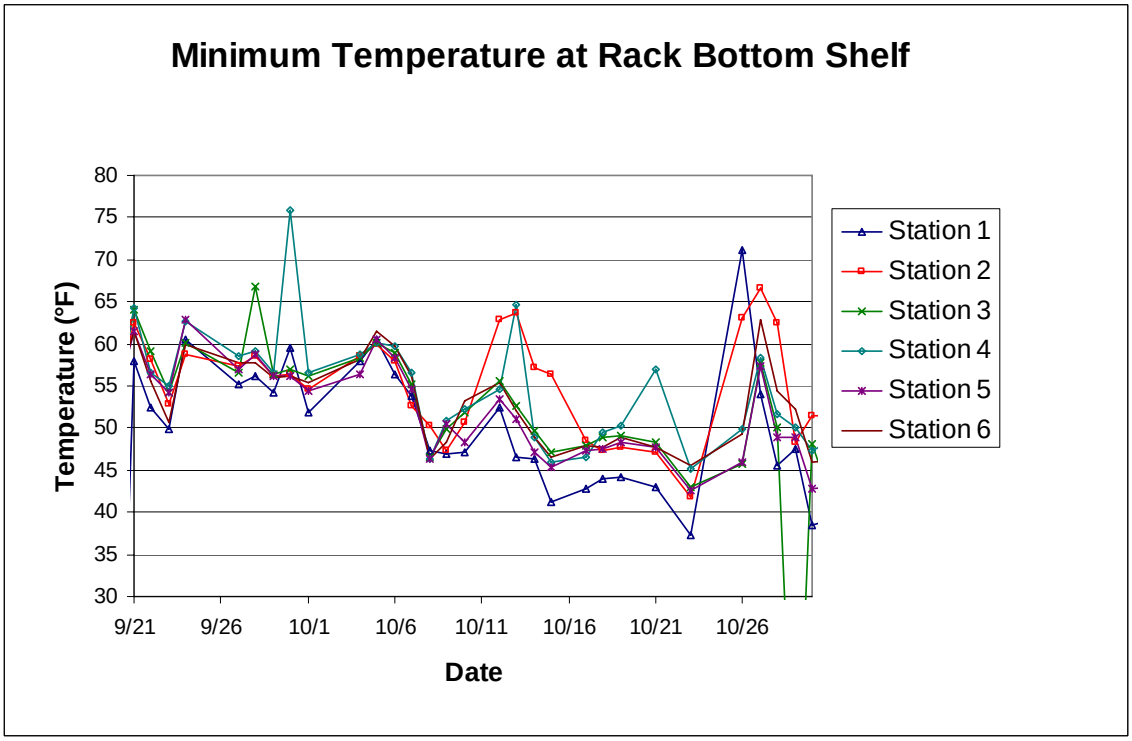

Figure 4-4 Minimum temperatures recorded near rack bottom shelf locations of the min/max sensor units from 9/21/04-10/31/04.

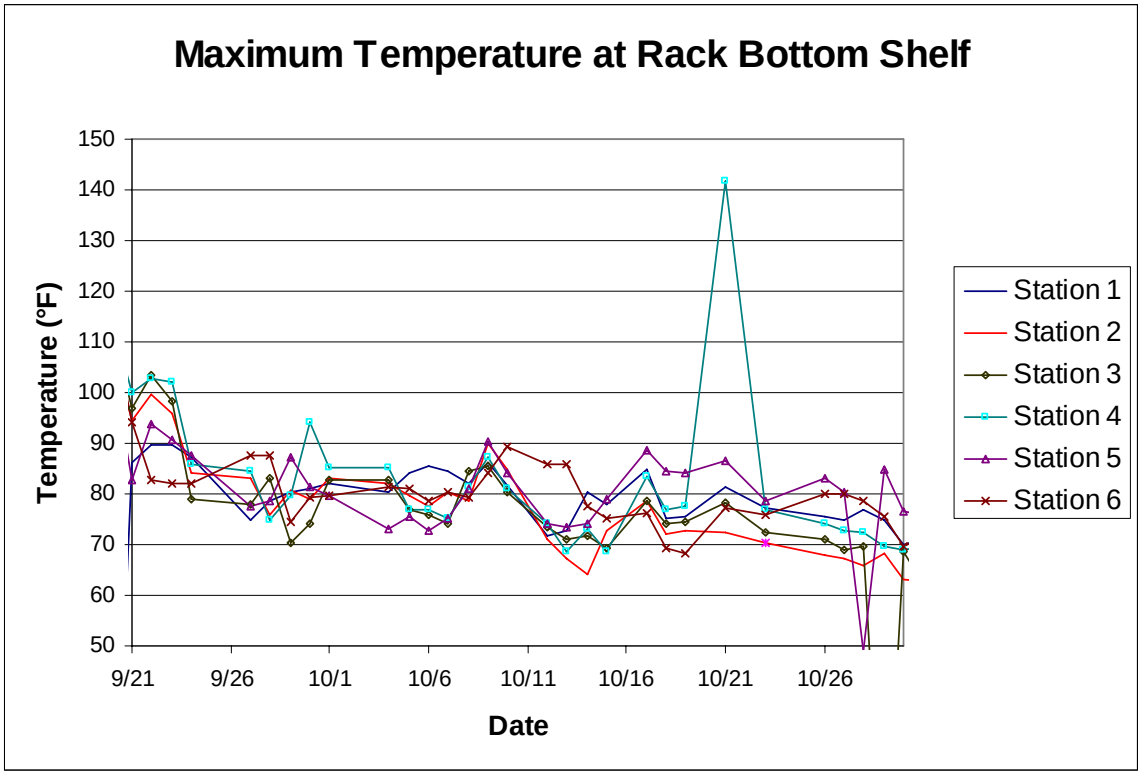

Figure 4-5 Maximum temperatures recorded near rack bottom shelf locations of the min/max sensor units from 9/21/04-10/31/04.

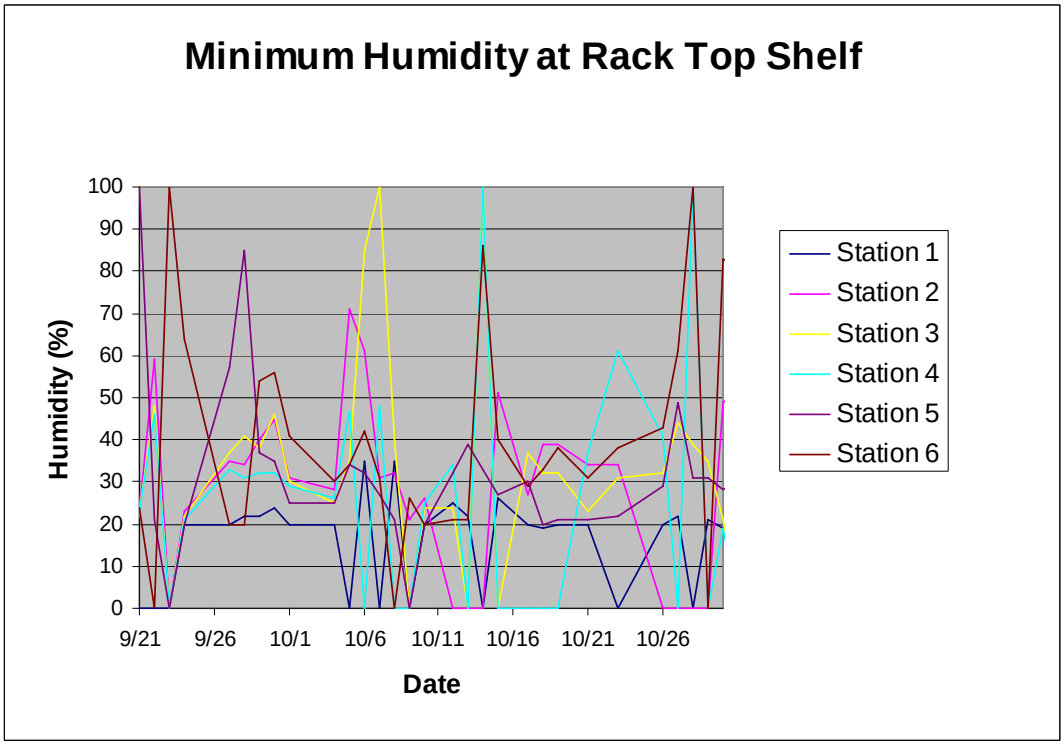

Figure 4-6 Minimum relative humidity recorded near rack bottom shelf locations of the min/max sensor units from 9/21/04-10/31/04.

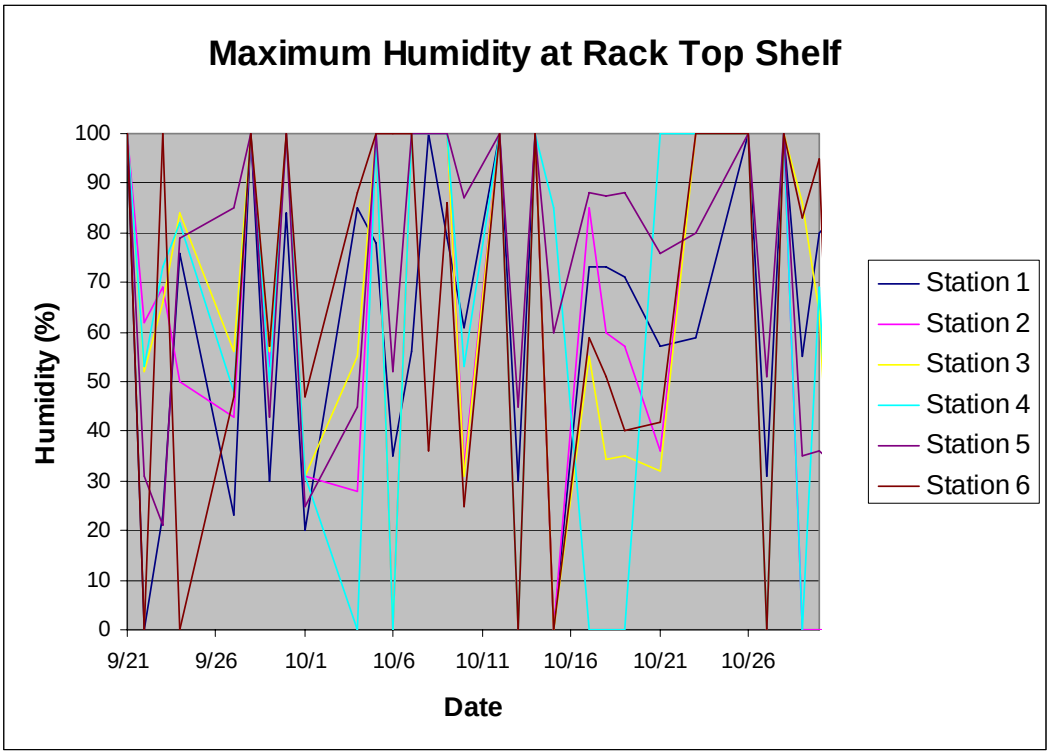

Figure 4-7 Maximum relative humidity recorded near rack bottom shelf locations of the min/max sensor units from 9/21/04-10/31/04.

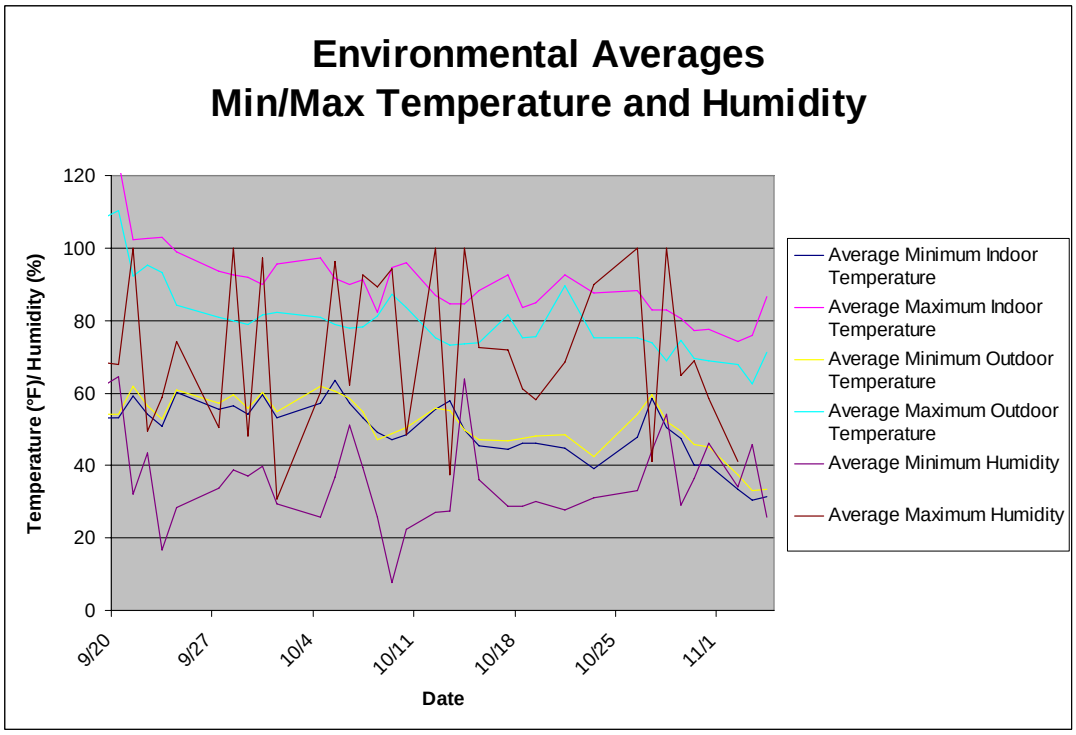

Figure 4-8 Average minimum and maximum temperature and humidity readings for all Min/Max sensor stations from 9/20/04-11/04/04. "Indoor" refers to recordings near top rack shelf. "Outdoor" refers to recordings near bottom rack shelf.

4.2 Operational Issues

Several problems were encountered during the construction, operation and analysis phases of this project. The most significant issue with the produced forage was mold formation during initial operations in August. Mold is a fungus that thrives in warm, damp environments. The hot and humid conditions in August during the initial weeks of operation contributed to a large fraction of the produced forage having mold. Figure 4-9 compares typical mold-infested forage with healthy forage.

Experts at NMSU provided analysis and recommendations based on inspection of samples of moldy forage from the greenhouse. The NMSU report is attached as Section 8.2 Appendix B. The mold problem may have been contributed to by the fly infestation that existed in the greenhouse at the time. Poor water quality may have also contributed, as discussed earlier. Maintaining cleanliness and disinfection to the extent possible were among the NMSU recommendations. Following the water system modifications and tray cleaning discussed earlier, the operations were resumed in September with daily water treatments using swimming pool chemicals. These included dry acid to correct the pH and chlorine to kill the pathogens. This significantly reduced the fly and mold problem. The seasonal change toward cooler weather during that time may have also helped.

The scale of project operations was reduced in September due to time limitations for on-site support by the UTEP student team. Hence, we used only a fraction of rack space and trays available for actually growing forage which made precise interpretation of water use and forage production performance more difficult. Another source of error was control of the irrigation system, which was far from ideal. For example, more lines remained active than needed for the number of trays and rack levels actually used in growing forage. Furthermore, the spray irrigation system needed better adjustment, which the tight schedule and remote site logistics made impossible to do. It was obvious that too much water was wasted by not having proper nozzle spray coverage, and by not having good on/off control to optimize performance. For example, some trays were kept too wet (promoted mold and/or rotting) while others got too dry and did not grow well, as shown in Figure 4-10a. Excess water spray from the irrigation system caused excessive wetting of the racks and the floor and contributed to problems such as shown in Figure 4-10b, where water leaked into a sensor mote due to a poor seal at the antenna feed-through connector in the mote enclosure.

(a) **(b)**

Figure 4-9 (a) Forage with mold infestation; (b) Healthy forage.

(a) **(b)**

Figure 4-10 (a) Non-uniform forage growth in places from problems with irrigation spray adjustment and/or control; (b) Water leak into sensor mote from broken seal.

5 Forage Nutrition Content Analysis and Assessment

Information is sparse [1-6] on the nutritional value of hydroponic forages for livestock, making it difficult to balance livestock diets and to compare and contrast the performance of hydroponic forage production from a variety of cultivars with conventional forage production. Other concerns include suitability, palatability, and overall impact of hydroponically grown forage on animal performance.

To address the nutritional issues, Sandia contracted with Dr. Clint Loest, Assistant Professor of Ruminant Nutrition in the Department of Animal and Range Sciences at New Mexico State University in Las Cruces. Dr. Loest and graduate student Justin Waggoner provided laboratory assessment of the nutrition content of forage samples taken periodically from the Santa Teresa greenhouse. Dr. Loest was also available to establish testing protocols and provide assessment support for livestock testing. However, the relatively short time-frame and limited resources available for this project did not permit doing controlled livestock performance testing.

Assessing the nutritional content and suitability of the forage product as a function of growth conditions and cultivar(s) used was of interest for comparison of growth performance in the greenhouse and to identify possible nutritional advantage to be gained with certain seed types. Forage samples correlated to crop tray monitoring sites physically distributed throughout the CEA facility were periodically taken and analyzed for nutrition content and suitability, as described in the remainder of this section.

5.1 Analysis Objectives

Samples of forage grown from the various types of seed being used were collected several times per week from different physical locations within the greenhouse over approximately a five week period. Sampling was done by harvesting approximately 25% of the contents of selected trays. Each sample was put into separate plastic containers with lids to reduce moisture loss. Date, time, cultivar type, age of the forage (days since germination), and physical location within the greenhouse were recorded. The samples were then picked up and transported to Las Cruces for freezer storage and later analysis at NMSU laboratory facilities. To maintain sample freshness and reduce deterioration, effort was made to minimize the time between harvesting samples and freezer storage at NMSU.

Objective 1: To determine the nutrient composition of forages from a controlled environment agriculture system. This was addressed by analytical laboratory experiments. Hydroponic forage samples were collected from the controlled environment agriculture system at Santa Teresa, NM and chemically analyzed for concentrations of dry matter (DM), crude protein (CP), acid detergent fiber (ADF), neutral detergent fiber (NDF), total digestible nutrients (TDN), calcium (Ca), phosphorus (P), magnesium (Mg), sodium (Na), iron (Fe), zinc (Zn), copper (Cu), and manganese (Mn). The forages were collected approximately twice a week over a 4-to 5-week period. Project operations staff assisted in the acquisition of samples from 12 different rack and tray locations within the greenhouse to evaluate possible changes in nutritional

composition as a function of tray location. Initially, two samples each were taken for the six different types of forage cultivar being grown at the beginning of the project. The cultivars being grown were later reduced from six to three, at which point the sampling was changed to four samples each for the three different types of cultivar. A nutrient profile from approximately 102 samples (96 forage growth samples plus 6 unsprouted seed samples from the different types used in the forage growth investigations) were determined. The six seed types were: barley, corn, oats, sorghum, triticale, and wheat.

Objective 2: To determine the benefits and/or limitations of feeding forages from a controlled environment agriculture system to cattle. This objective was addressed by comparing the nutrient requirements for growing beef cattle [7] to the nutrient composition of the forages analyzed for Objective 1.

5.2 Analysis Approach and Results

Objective 1: Sandia's forage production system operations staff provided the Nutrition Lab at NMSU with 4 forage samples each of oats, sorghum, and wheat, 27 samples each of barley and triticale, and 26 samples of corn. Location within the same controlled environment agriculture system had no significant affect on nutrient composition of forages, and therefore, the mean nutrient composition of the 6 different types of forage cultivars being grown within the same controlled environment agriculture system are presented in Table 5-2.

The concentration of DM for the forage cultivars was greatest ($P < 0.01$) for oats, and lowest ($P < 0.01$) for barley and triticale, whereas the concentration of CP (expressed as % of DM) was greatest ($P < 0.01$) for wheat and lowest ($P < 0.01$) for corn and oats. The concentrations of fiber (ADF and NDF as % of DM) were greater ($P < 0.01$) for barley and triticale when compared to corn, oats, sorghum and wheat. In contrast, total digestible nutrients (TDN) were lowest ($P < 0.01$) for barley and triticale, and greatest ($P < 0.01$) for corn. In general, triticale and wheat had the greatest concentrations of macro minerals and trace minerals, whereas corn and oats had the lowest mineral concentrations.

One unsprouted seed sample was analyzed for each of the six different seed types used in the project. The nutrient composition of the seed samples are presented in Table 5-1. Concentrations of CP, ADF, and NDF increased numerically when seeds sprouted into hydroponic forage. Similarly, concentrations of macro- and trace minerals were numerically greater in the forages when compared to the seeds of the same cultivar. It is likely that the carbohydrate stored as starch (not analyzed) in the seeds was used to increase the synthesis of fiber in the sprouted forages.

Objective 2: The nutrient requirements and the nutrient supply by various forages for a 700 lb beef steer (gaining either 1.0 or 1.5 lb/day) with a dry matter intake of 2% of its body weight are presented in Table 5-3. In general, daily DM intake of cattle will range from 2.0 to 2.5% of their body weight. To obtain this intake level, the steer would have to consume more than 70 lb/day of hydroponic forage (approximately 182, 87, 71, 97, 187, and 110 lb/day for hydroponic barley, corn, oats, sorghum, triticale, and wheat,

respectively), which is greater than the feed intakes required for traditional feeds (approximately 50, 56, and 39 lb/day for fresh alfalfa, wheat pasture, and corn silage, respectively) to obtain the same level (14 lb/day) of dry matter intake (Table 5-3).

The high feed intakes required for the hydroponic forages are due to their high moisture concentrations (or low DM concentrations). However, assuming that the steer can consume the large amounts of feed, then the CP and TDN requirements for a steer gaining 1.0 lb/day will be met by almost all the hydroponic forage cultivars (except TDN for barley). Figures 5-1 through 5-8 compare nutrient composition of the hydroponic forages to alfalfa, corn silage and wheat pasture. Ca and P are important minerals for growing cattle, and the Ca:P ratio for cattle must exceed 1:1, with a 2:1 ratio being recommended. For all the hydroponic forages, the Ca:P ratio is less than 1:1, and therefore a Ca supplement will be required if cattle were to be fed these forages.

To summarize this chapter, the hydroponically-grown forages freshly sampled from the greenhouse system contained large amounts of moisture. Consequently, cattle would have to consume larger volumes of these forages as-harvested to meet their nutrient requirements. On the other hand, the cattle would need and consume less water by virtue of the water intake from the forage.

5.3 References

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Table 5-1 Nutrient composition of unsprouted seed samples for different forage types.

	Unsprouted Seed					
Item	Barley	Corn	Oats	Sorghum	Triticale	Wheat
Observations	1	1	1	1	1	1
Nutrient	---------- % of as is ----------					
DM	90.6	89.3	92.6	89.6	89.9	89.9
	---------- % of DM ----------					
CP	13.7	10.0	11.4	11.9	14.8	16.9
ADF	8.1	3.7	10.3	5.5	4.7	3.2
NDF	16.7	6.7	35.6	7.5	10.1	12.1
	---------- % of DM ----------					
Ca	0.06	0.01	0.09	0.02	0.08	0.07
P	0.29	0.32	0.37	0.38	0.52	0.46
Mg	0.11	0.11	0.13	0.15	0.16	0.15
Na	0.015	0.000	0.002	0.001	0.001	0.001
	---------- ppm of DM ----------					
Fe	94	46	99	69	54	70
Zn	23	18	19	18	34	34
Cu	7	2	5	6	5	6
Mn	16	5	52	13	40	38

Table 5-2 Nutrient composition of forages grown in a controlled environment agriculture system.

	Hydroponic Forage						
Item	Barley	Corn	Oats	Sorghum	Triticale	Wheat	SEM
Observations	27	26	4	4	27	4	
Nutrient	---------- % of as is ----------						
DM	7.7[a]	16.1[c]	19.6[d]	14.5[bc]	7.5[a]	12.7[b]	1.15
	---------- % of DM ----------						
CP	20.6[b]	15.1[a]	14.4[a]	20.1[b]	22.9[c]	27.8[d]	1.39
ADF	34.0[d]	12.2[a]	20.6[b]	13.5[a]	31.3[c]	21.0[b]	1.76
NDF	60.9[c]	29.1[a]	33.5[ab]	25.1[a]	60.2[c]	40.0[b]	3.57
TDN	61.3[a]	71.6[d]	64.8[bc]	68.1[c]	61.9[a]	63.8[ab]	0.91
	---------- % of DM ----------						
Ca	0.30[b]	0.08[a]	0.18[ab]	0.21[ab]	0.46[c]	0.30[b]	0.045
P	0.47[ab]	0.40[a]	0.43[ab]	0.66[bc]	0.93[d]	0.82[cd]	0.067
Mg	0.16[a]	0.15[a]	0.13[a]	0.25[b]	0.25[b]	0.25[b]	0.018
Na	1.48[b]	0.40[a]	0.40[a]	0.61[a]	1.51[b]	0.72[a]	0.240
	---------- ppm of DM ----------						
Fe	101.5[b]	45.4[a]	110.4[bc]	104.9[bc]	129.4[c]	108.5[bc]	12.5
Zn	40.8[ab]	29.9[a]	25.4[a]	40.7[ab]	81.3[c]	63.3[bc]	8.7
Cu	9.9[c]	1.9[a]	5.5[ab]	8.3[bc]	12.3[d]	11.8[cd]	1.3
Mn	23.7[b]	4.7[a]	45.9[c]	28.6[b]	68.8[d]	61.5[d]	4.2

[abc] Means in rows with different superscripts differ ($P < 0.01$)

Table 5-3 Nutrient requirements and the nutrient supply by various forages for a 700 lb beef steer (gaining either 1.0 or 1.5 lb/day) with a dry matter intake of 2% of its body weight.

	Steer requirement for:		Traditional Feeds			Hydroponic Forage					
	1.0 lb/day gain	1.5 lb/day gain	Alfalfa, fresh	Wheat pasture	Corn silage	Barley	Corn	Oats	Sorghum	Triticale	Wheat
Intake (lb/day) of:											
Total feed	-	-	50	56	39	182	87	71	97	187	110
DM	14	14	14	14	14	14	14	14	14	14	14
CP	1.40	1.68	2.80	2.52	1.12	2.88	2.11	2.02	2.81	3.21	3.89
TDN	8.68	9.52	8.40	9.66	9.80	8.58	10.02	9.07	9.53	8.67	8.93
Ca	0.056	0.070	0.224	0.048	0.036	0.042	0.011	0.025	0.029	0.064	0.042
P	0.028	0.035	0.042	0.049	0.031	0.066	0.056	0.060	0.092	0.130	0.115

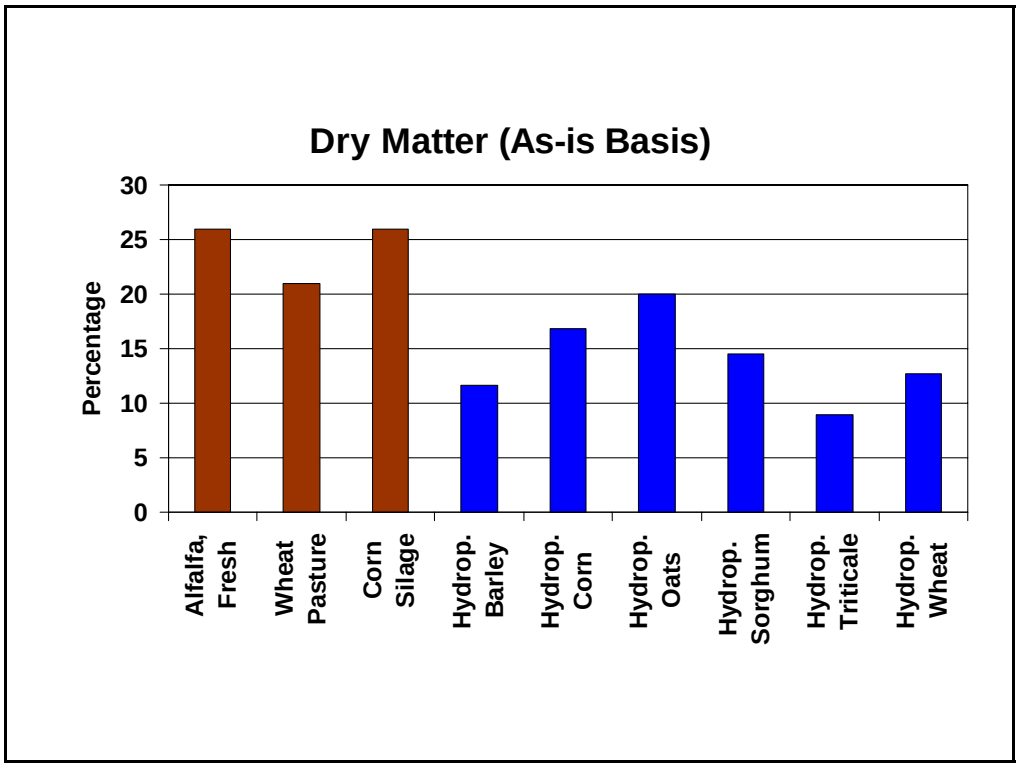

Figure 5-1 Dry Matter Content Comparison: Conventional vs. Fresh-Harvest Hydroponic Forage.

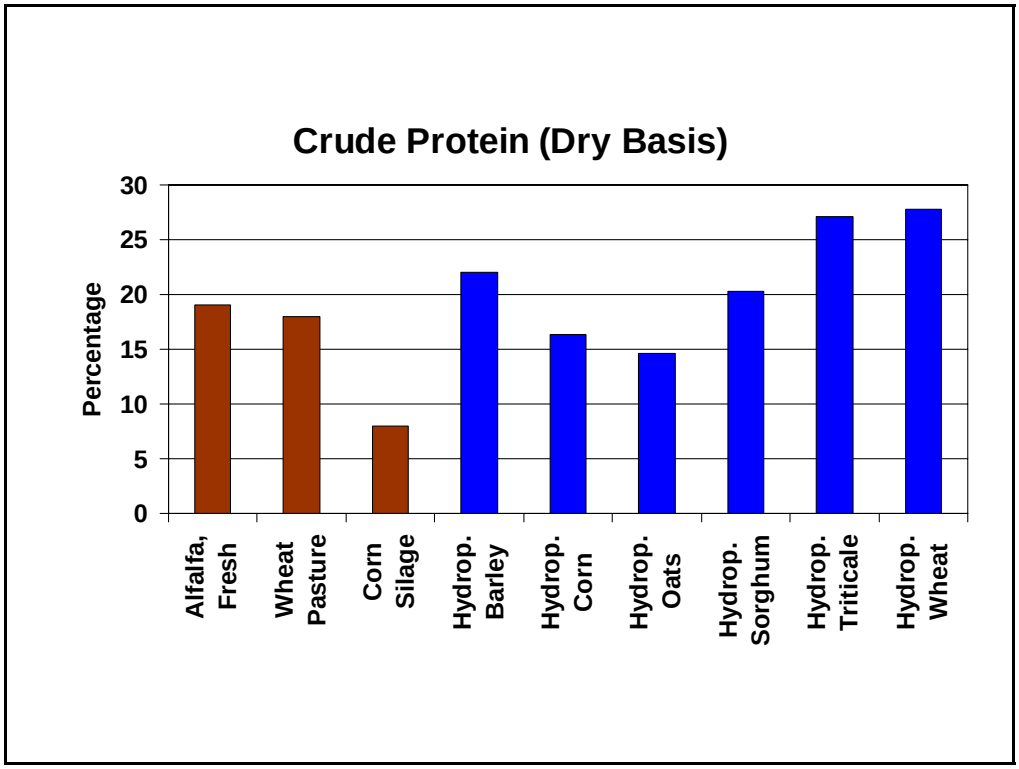

Figure 5-2 Crude Protein Content: Conventional vs. Hydroponic Dry-Weight Equivalent Forage.

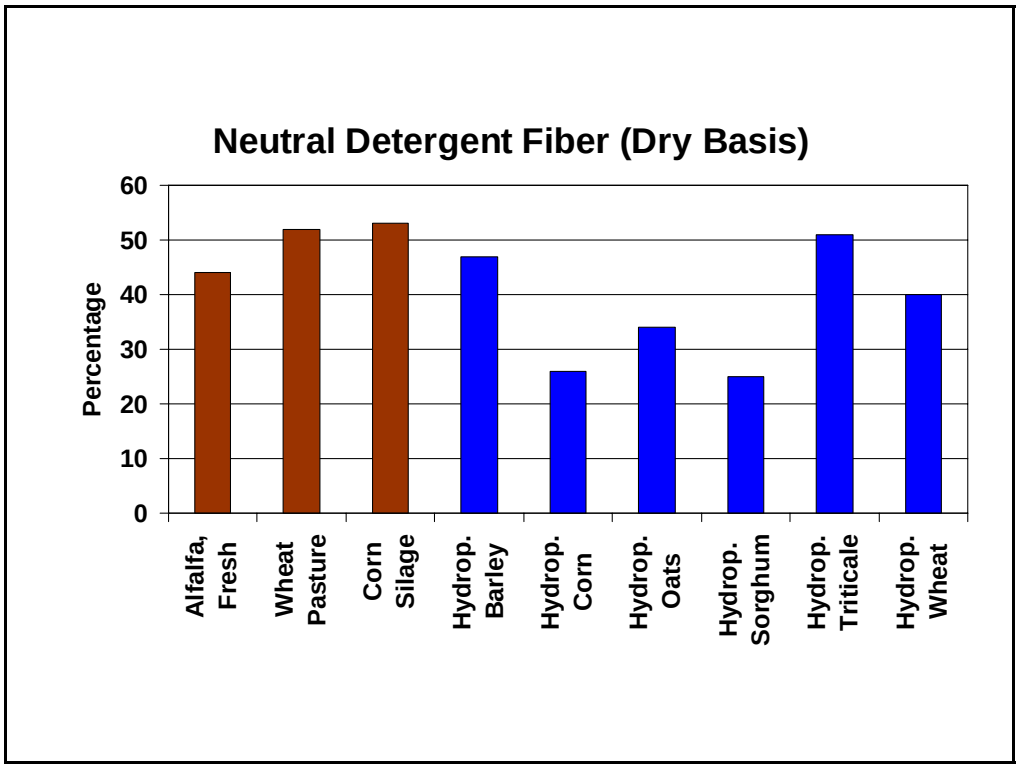

Figure 5-3 Neutral Detergent Fiber Content: Conventional vs. Hydroponic Dry-Weight Equivalent Forage.

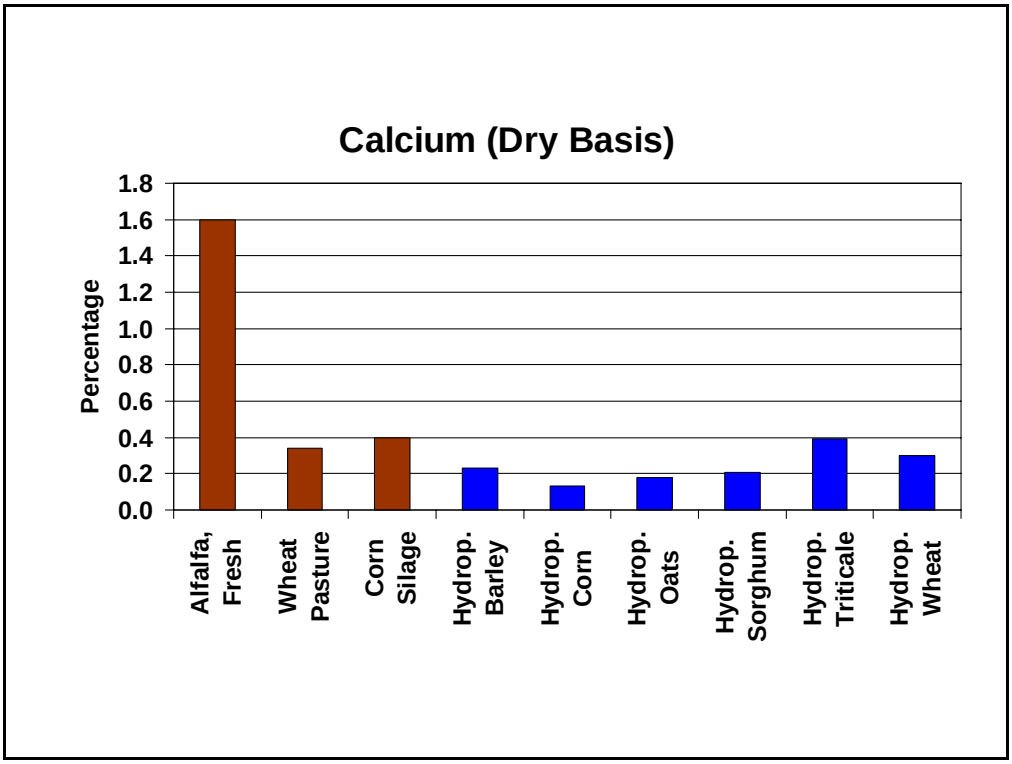

Figure 5-4 Calcium Content: Conventional vs. Hydroponic Dry-Weight Equivalent Forage.

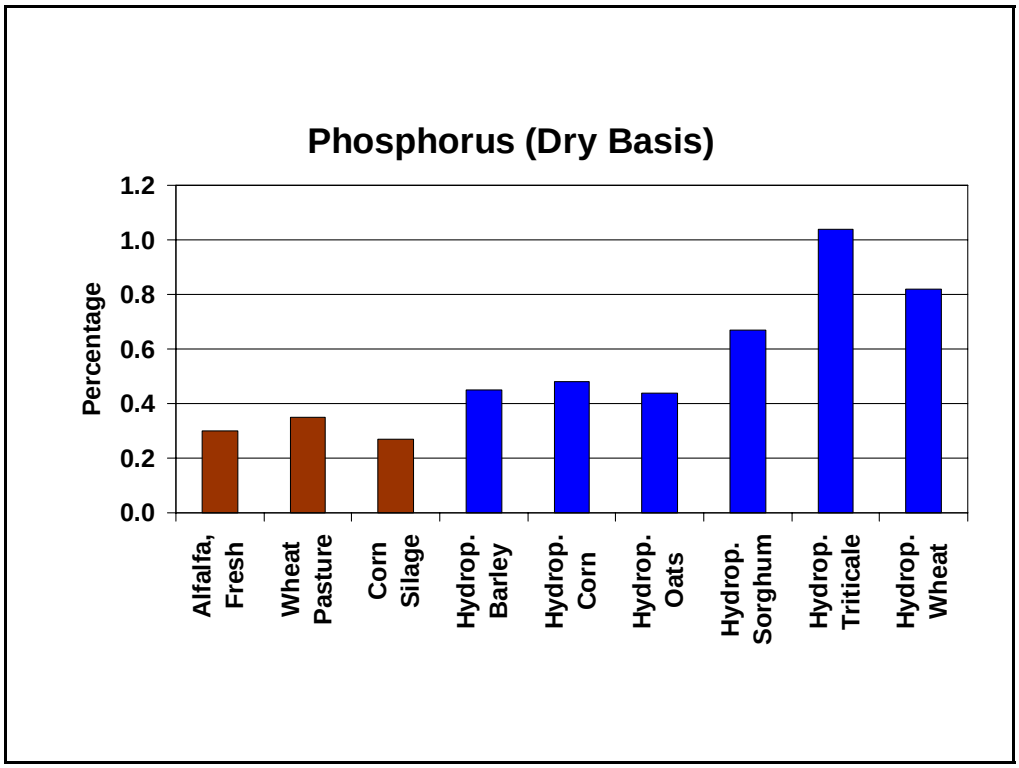

Figure 5-5 Phosphorus Content: Conventional vs. Hydroponic Dry-Weight Equivalent Forage.

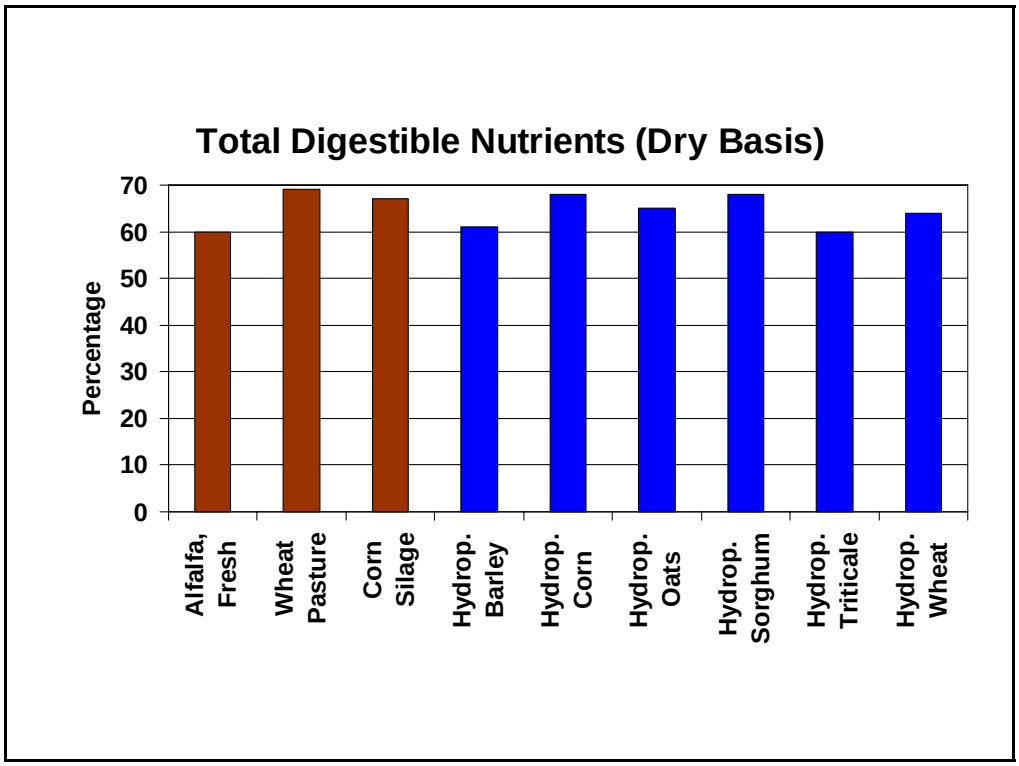

Figure 5-6 Total Digestible Nutrient Content: Conventional vs. Hydroponic Dry-Weight Equivalent Forage.

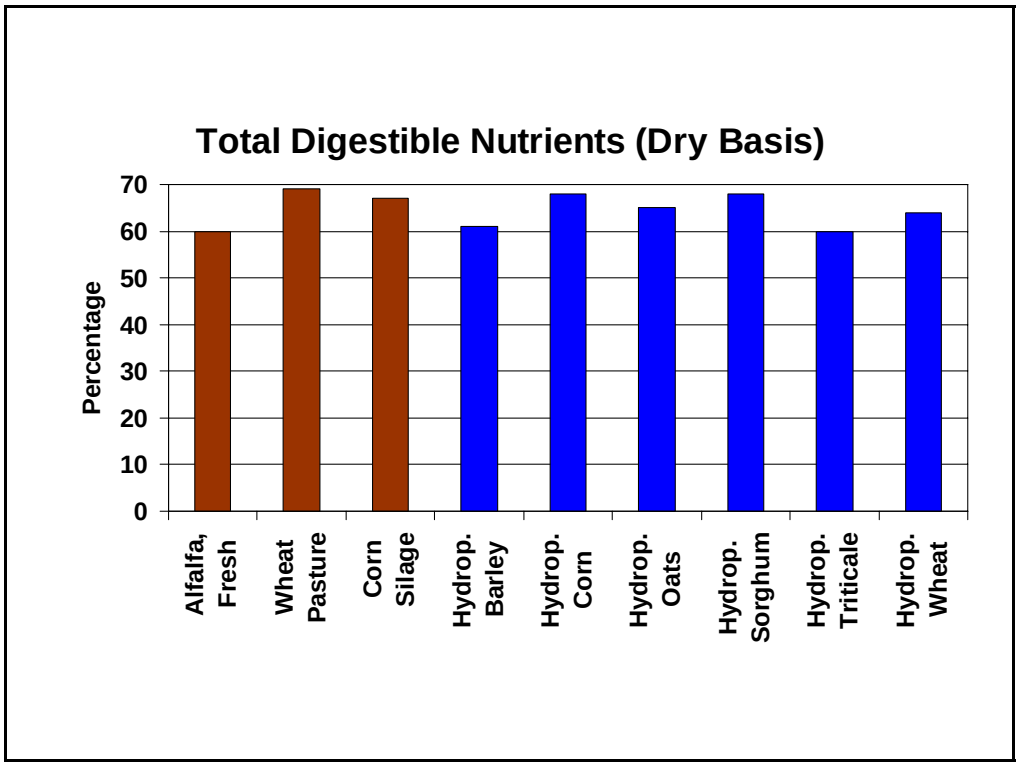

Figure 5-7 Total Digestible Nutrient Content: Conventional vs. Hydroponic Dry-Weight Equivalent Forage.

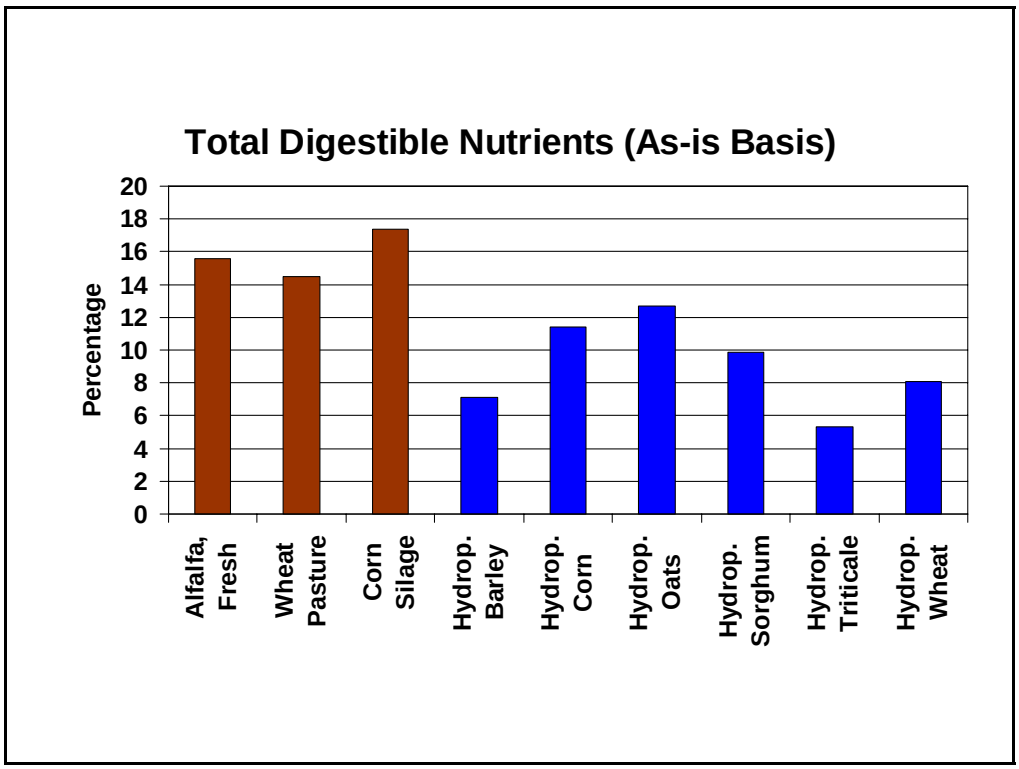

Figure 5-8 Total Digestible Nutrient Content: Conventional vs. Fresh-Harvest Hydroponic Forage.

6 Wireless Sensor System Data Analysis and Visualization

In this section we present and discuss environmental data captured by the wirelessly-networked sensor system introduced earlier in Section 3-4. The Crossbow sensor system units, which we also interchangeably refer to as sensor "motes" or sensor network "nodes", each contain a suite of sensors that measure different environmental parameters of interest. This multi-sensor suite (hence the term "multi-modal sensing") includes temperature, relative humidity, light (visible and IR), and atmospheric pressure. There are two humidity sensors and one atmospheric pressure sensor. Each of these three sensors has paired with it a co-located temperature sensor that provides the means for temperature correction of the humidity and pressure sensor measurements.

One humidity and temperature sensor pair is sealed within the mote enclosure without direct access to the exterior environment. This sensor pair provides what we call the "interior humidity" and "interior temperature" data. The second humidity & temperature sensor pair is located on the bottom sensor board adjacent to a port in the sealed enclosure. The port is designed with a moisture seal that allows those two sensors to have direct access to the exterior ambient environment while providing weather seal protection for the interior of the mote. This sensor pair provides what we call the "exterior humidity" and "exterior temperature" data. The pressure sensor and its co-located temperature sensor are similarly situated above a port in the bottom side of the sealed enclosure that provides access to the external environment while providing weather seal protection for the mote interior. Data from this co-located pressure and temperature sensor pair is not presented here due to a software problem that caused those data fields to be zero-filled during the data capture period referenced in this section. The four light sensors consisted of two co-located pairs, one pair on the top sensor board mounted below the sealed window in the top of the case, and one pair mounted on the bottom sensor board and located above the sealed window in the bottom of the case. The top pair consisted of an IR sensor (Photo-1 data) and a visible sensor (Photo-2 data). The bottom pair consisted of an IR sensor (Photo-3 data) and a visible sensor (Photo-4 data). The battery voltage inside the mote is also sensed to allow monitoring of battery status.

Data from all of the mote sensors was sampled, packaged, time-stamped, and wirelessly sent to the Stargate unit by each mote in the network every 15-seconds. The frequency of this sampling is adjustable with software. The maximum sampling rate for the overall network will be dictated by the time required for all of the motes within the network to "report" their data to the Stargate. This will be a function of the number of nodes (motes) in the network and the amount of routing "hops" required to get data from each node to the Stargate. For the configuration used in this project, each node was able to send data directly to the Stargate without the need for multi-hop routing through other nodes. This, along with the relatively small number of nodes involved, allowed for relatively rapid sampling. We chose to use the 15-second sampling increment for these initial project investigations to provide sub-minute time resolution. An additional tradeoff consideration is battery lifetime for the sensor motes. Higher sampling rates require more frequent transmission of data by each sensor mote, which consumes more power

and lowers the operational lifetime of the mote battery. For this project, mote battery size was selected to insure adequate capacity for several months of continuous operation at the 15-second sampling rate. Maximum battery lifetime is not precisely known at this point, and could not be determined with the limited resources and duration of this project.

The remainder of this section focuses on the analysis and visualization of environmental data captured during the continuous seven day period of October 21-27, 2004. We note in passing that this effort was limited by project time and resource constraints to what might best be termed as preliminary analysis and demonstration. Among the issues yet to be addressed is calibration of sensors within and among the mote systems. This is not an insignificant issue, but was beyond the resources and scope of this project. We simply assume for the time being that the sensors and compensation circuitry within and among the packaged Crossbow motes used in this project were reasonably well matched and provided reasonably accurate measurements of the environmental parameters being sampled. This has not yet been independently verified or quantified.

6.1 Data Processing and Analysis

The data collected by the Stargate unit and remotely linked to Sandia via a secure file copy protocol arrives in comma delimited form. An example snippet of data records from one of these files is shown below in Figure 6-1.

⋮	...
Record N	2004-09-18 11:24:42.455294,3,0,0,1652,32.618671,39.568802,19.736279,39.264999,54,201,216,135,0.000000,0.000000
Record N +1	2004-09-18 11:24:42.840971,3,0,1,0,0,0,0,0,0,0,0,0,38.687889,863.089783
Record N + 2	2004-09-18 11:24:43.281922,27,0,2,1643,29.570358,41.881599,18.038748,41.332802,70,206,12,137,0.000000,0.000000
Record N + 3	2004-09-18 11:24:43.443467,100,0,3,1652,30.301250,38.971001,20.922720,38.637798,50,196,212,120,0.000000,0.000000
Record N + 4	2004-09-18 11:24:44.023621,53,0,4,1652,33.804821,39.833401,20.514580,39.480598,67,208,8,129,0.000000,0.000000
Record N + 5	2004-09-18 11:24:44.173455,32,0,5,1634,38.563583,38.578999,21.276218,38.187000,60,205,7,129,0.000000,0.000000
Record N + 7	2004-09-18 11:24:44.353763,4,0,6,0,0,0,0,0,0,0,0,0,34.370117,867.909973
Record N + 8	2004-09-18 11:24:44.544463,52,0,7,0,0,0,0,0,0,0,0,0,34.836132,865.388794
Record N + 9	2004-09-18 11:24:44.737171,59,0,8,0,0,0,0,0,0,0,0,0,142.006058,730.671753
⋮	...

Figure 6-1 Data File Snippet from the Stargate System.

The received data was then processed and configured into time series data files for the following environmental parameters at each node in the network:

Parameter 1: battery voltage
Parameter 2: external humidity
Parameter 3: external humidity temperature
Parameter 4: internal humidity
Parameter 5: internal humidity temperature
Parameter 6: photo 1 (top side, IR)
Parameter 7: photo 2 (top side, visible)
Parameter 8: photo 3 (bottom side, IR)
Parameter 9: photo4 (bottom side, visible).

All of the data processing was done in Matlab. There were three main tasks necessary for the initial analysis and visualization: 1) read in the data files, 2) clean the data, interpolate, and save in a Matlab standard form, and 3) post-process and visualize. Each of these tasks were written into separate Matlab scripts and these scripts are given in Section 8.5 Appendix E. The script to read in the data files was extremely simple. Matlab has a built in file reading function called "textread" which can read in a text file with a known and given format. Since the format of each line of the data files was static, simply one call to the textread function needed to be made, and results were stored sequentially into the following column vectors: year, month, day, hour, min, sec, nodeid, parent, epoch, voltage, ext_hum, ext_hum_temp, int_hum, int_hum_temp, photo1, photo2, photo3, photo4, press_temp, pressure. These column vectors were then concatenated into a single data matrix, at which point the data read in was complete.

The second main task was to clean the data, interpolate it, and save it in a Matlab standard form. The "cleaning" of the data simply involved removing unwanted zeros in the data before interpolating. As can be seen in the data snippet shown in Figure 6-1, there were two primary types of data readings: one which always had zeros for press_temp and pressure, and one which always had zeros for voltage, ext_hum, ext_hum_temp, int_hum, int_hum_temp, photo1, photo2, photo3, and photo4. This was an unfortunate side effect of the method that the motes used to report data. To generate a valid interpolation, all of these zero fields had to be removed from the data to be interpolated.

The data also needed to be matched to a specific location in time and space. Although the time of each reading was reported in the data files, the location of each reading was not. The only way of matching a reading to a location was through the node ID which reported the reading. An additional file (given in Section 8.5 Appendix E) was created listing the sensor IDs and locations. The node IDs reported in each reading were matched against the known node IDs and spatial deployment, and only the matching readings were parsed out and passed onto the interpolation, now complete with spatial information.

The data was initially simply interpolated using the Matlab function "griddatan". Using about 500,000 points for interpolation, the code took about 7 hours to run per sensor to

compute the interpolation. Since the eventual goal of this activity might be to use the collected data for a real-time feedback application, a run-time of 7 hours is obviously unacceptable. This problem was caused because the data as given in the files from the Stargate could not be considered completely regularly spaced. While the x, y, and z positions of the deployment formed a regular grid in the greenhouse, not all nodes reported at exactly the same time, and therefore the readings were not regular along the time dimension. This required the use of a much more timely interpolation algorithm even though the algorithm was only for linear interpolation.

In order to alleviate the run-time problem, the time dimension was thus regularized. Since all the nodes reported in 15 second intervals, the time coordinate was simply rounded to the center of the nearest 15 second interval. This gives a maximum deviation between actual reading time and regularized reading time of only 7.5 seconds, and it seems a reasonable assumption that the data being sensed would not change significantly in this period.

Once the time dimension was regularized, all of the four dimensions specifying the location of a sensor reading were regular, and a much faster interpolation method could be used. The data was also converted from its initial 2 dimensional form into a 4 dimensional form which is the necessary format for Matlab to accept data into its interpolation function “interpn”. For the same number of points, 500,000, the entire interpolating process took less than 10 seconds to complete per sensor on the regularized data. The Matlab standard .mat form was used to save the interpolated data for future use with the visualization script.

Finally, the third main task was that of post-processing the data and actually visualizing it. There were really two major parts of this final task: one to visualize the greenhouse and sensor locations, and the other to visualize the interpolated data in the framework of the greenhouse. In order to visualize the greenhouse and sensor locations, two additional files specifying the spatial orientation of the green house and each sensor location within the greenhouse were created. Two scripts were also created to 1) read in the information from these geometry files and 2) to plot the information on a 3-dimensional coordinate system. All four of these files, the two geometry files and the two scripts, are given in Section 8-5 Appendix E and Section 8-7 Appendix F.

An example of the resulting time series data for the nine parameters discussed earlier is shown in Figure 6-2 for one of the sensor motes (ID #13). For reference and comparison, these nine channels of time series data are presented in Section 8.3 Appendix C for all 27 sensor motes deployed in the greenhouse.

Figure 6-3 shows the locations and corresponding ID numbers for the 27 sensor motes deployed within the (x, y, z) coordinate system of the greenhouse. Comparing this with the sensor locations shown in Figure 3-3, one can see that sensor motes #28, #29 and #50 are mounted adjacent to the min/max sensor #4, sensor motes #34, #57 and #4 are adjacent to min/max sensor #3 and sensor motes #46, #32, and #42 are adjacent to min/max sensor #2. Figure 6-4 presents overlay scatter plots showing the correlation

between data from min/max sensors #1, #2, & #3 and the minimum and maximum data points extracted from the time series data from sensor motes #46 and #34. Several additional correlation scatter plots are provided in Section 8.4 Appendix D. We see from Figure 6-4 that the min/max probe data and the extremes in the time series data from nearby sensor motes do not exactly agree, but seem to generally show similar scatter trends. Further examination of the differences seen is needed, but could not be pursued within the time and resource constraints of this project.

Closer examination of the time series data in Figure 6-2 reveals several interesting observations. The battery voltage in the mote appears to correlate very strongly with temperature. This suggests a thermal effect on voltage due to battery heating during the day. Since there seemed to be a strong relation between the voltage and temperature, we suspected other correlations, such as humidity and temperature or light and temperature, or IR light with visible light, etc. To analyze this, a correlation between all sensors on a single mote for every mote was calculated and the results averaged together. Essentially, this is the correlation coefficient (ρ^2) for scatter plots of every sensor versus every other sensor. The matrix of all the results is given in Table 6-1:

Table 6-1 Average correlation coefficient (ρ^2) matrix for the wireless sensor motes.

Correlation Coefficient ρ^2	**Battery Voltage**	**Relative Humidity #1**	**Temp #1**	**Relative Humidity #2**	**Temp #2**	**Photo #1**	**Photo #2**	**Photo #3**	**Photo #4**
Battery Voltage	1.0000	-0.1606	0.9160	-0.4702	0.8858	0.5516	0.6183	0.4272	0.5764
Relative Humidity #1	-0.1606	1.0000	-0.2143	**0.5389**	-0.2164	-0.2507	-0.2674	-0.2443	-0.3118
Temp #1	0.9160	-0.2143	1.0000	-0.5333	0.9600	0.7082	0.7717	0.5630	0.7396
Relative Humidity #2	-0.4702	**0.5389**	-0.5333	1.0000	-0.4967	-0.4281	-0.4640	-0.3538	-0.4728
Temp #2	0.8858	-0.2164	0.9600	-0.4967	1.0000	0.6821	0.7450	0.5463	0.7143
Photo #1	0.5516	-0.2507	0.7082	-0.4281	0.6821	1.0000	0.9174	0.7334	0.8858
Photo #2	0.6183	-0.2674	0.7717	-0.4640	0.7450	0.9174	1.0000	0.6540	0.8851
Photo #3	0.4272	-0.2443	0.5630	-0.3538	0.5463	0.7334	0.6540	1.0000	0.8606
Photo #4	0.5764	-0.3118	0.7396	-0.4728	0.7143	0.8858	0.8851	0.8606	1.0000

The matrix shown in Table 6-1 is symmetric about the diagonal. The number in row i column j is the average correlation coefficient (ρ^2) for the time series data between sensor i and sensor j. The diagonal is all 1's because sensors are perfectly correlated with themselves. From Table 6-1 we observe the following:

1) Both temperatures are highly correlated
2) Voltage is very highly correlated to both temperatures
3) External humidity temperature is almost perfectly correlated to internal humidity temperature
4) Temperature is inversely correlated with humidity, weakly for external humidity, and moderately for internal humidity (this could mean that the temperature compensation in the sensors isn't working well, but this is unlikely since the correlation with other sensors is similar)
5) The internal and external humidity data are only moderately correlated with each other (i.e. it would seem that heat from outside gets inside relatively quickly, but it takes longer for the humidity to get in or external humidity never completely makes it inside because the weather seals are working well)
6) The photo sensors are all moderately correlated to voltage (probably indirectly), and a bit more strongly to temperature. They are also all weakly inversely correlated to humidity. Also, it seems they are all correlated a bit more strongly with internal parameters than external ones (interesting, but this might be spurious).
7) The photo sensors are all fairly strongly correlated with each other.

Correlation of data across space is also of interest, (i.e. the external humidity at one mote versus that at another), but this has been deferred until later due to funding and time limitations.

It is interesting to note in Table 6-1 that the data from the two relative humidity sensors within each mote are not particularly well correlated. The correlation coefficients for the two humidity sensors are the numbers shown in **bold** font in the Table 6-1 matrix at the (column-4, row-2) and (column-2, row-4) positions. Because of correlation matrix symmetry, the correlation coefficient is the same for each and has the value 0.5389.

Relative humidity (RH) is a measure of the ratio of the actual water content in a given sampled volume of air relative to the maximum water holding capacity of that same volume of air, which is a function of the temperature of the air volume. Due to the pairing of internal and external humidity and temperature sensors, it is instructive to look at the dew point calculation for each of the RH-Temperature sensor pair measurements.

The dew point (DP) for a given volume of air is a function of both the relative humidity and the temperature at which that relative humidity was measured for the air volume. Under standard atmospheric pressure conditions, the dew point can be determined from Eq.-1.

$$\text{Dew Point (DP)} = [(17.27 \times T) / (237.7 + T)] + \text{Ln (RH)}, \qquad \text{(Eq. 1)}$$

where T is temperature in degrees Celcius [°C], RH is relative humidity in percent, Ln(RH) is the natural logarithm of RH, and DP is in units of degrees Celcius [°C]. DP is the temperature at which the water vapor content within the given volume of air would condense out as liquid water.

If we calculate the dew point for both the internal and external RH-Temperature data pairs for all the motes, we find that for each mote they are almost identical. This results in an overall internal vs. external DP correlation coefficient average for all the motes of about .9444. Furthermore, DP has a strong POSITIVE correlation with the temperature, and a weak positive correlation with RH. (The RH has a moderate NEGATIVE correlation with temperature.). Hence, as the temperature of the sampled air goes up, the total amount of moisture it can hold goes up, and its actual content tends to go up. However, unless the actual moisture content keeps pace with temperature increases, the RH will decrease. This points out that the RH data alone does not relate all that well to the absolute amount of moisture in the air.

6.2 Data visualization

The visualization of the interpolated data was actually quite simple once all of the other steps had been performed. Examples are provided using four different visualization methods in Figures 6-5 through 6-8 for the case of the parameter “external temperature” over a 3.3-hour period during the morning of October 27, 2004. The four different visualizations chosen for these figures are: 1) filled contour, 2) isosurface, 3) parameter slices, and 4) parameter surfaces. All have corresponding Matlab functions: “contourf”, “isosurface”, “slice”, and “surfc”. Some of these Matlab functions had to be slightly edited, but for the most part, they could all be called directly. Since these functions expect 3 dimensional data, x, y, and z with no time, but the interpolated data was in 4 dimensions, including time, time lapse movies of the changing parameter fields could be made. Again, Matlab had built in functions to help create standard .avi movie format files.

The sequence of views shown as A, B, C, and D in each of the Figures 6-5 through 6-8 provide visualization of the “external temperature” parameter changing with time in 50-minute increments. These are essentially time-lapsed “snap-shots” of the visualized parameter taken every 50-minutes, beginning at 9:21-am and ending at 11:51-am on October 27. Each of the four figures, with their different visualization methods, show a warming trend with time, and an increase in temperature as a function of height (z) above the floor. Temperature gradients are also seen in the horizontal (x, y) dimensions as a function of time. These results are qualitatively reasonable, given the warming conditions one would expect as the morning sun rises and provides thermal gain within the greenhouse in going from morning to mid-day.

Although this initial interpolation and time lapse visualization of the data is quite informative in itself, there is still a large amount of computation that could be done on the data to provide much more useful information. First, much information on actual plant growth needs and response could be determined, assembled, and input into a

data structure. The growth information would contain items such as plant nutritional needs and response models, growth and yield models, time-dependent plant configuration and spatial density, etc.. These parameters could then be matched up against the known time series of the monitored environmental parameters at the locations of the plants to provide an indication as to how certain environmental histories affect plant growth. Optimum control of environmental conditions to achieve desired objectives could then be determined and finer-grained control systems could be implemented to maintain these conditions. Ultimately, cost/benefit analyses would be required to determine whether potential increases in plant growth and yield performance provided with finer-grained system monitoring and environmental control would be worth the additional cost it may require over traditional methods of more coarse-grained monitoring and environmental control in CEA.

Moreover, the initial deployment of sensor systems and data interpolation presented for this project does not take into account the inhomogeneities due to the presence of physical structures (racks, trays, plants, etc.) and their material constituitive properties. Higher-fidelity modeling/simulation combined with embedded and networked sensing/monitoring/response capability (i.e., SDAC functionality) of the complex physical system elements and their interactions with the broader environment (both within and immediately external to the greenhouse) is an area open for investigation and improvement. Particularly intriguing is the possibility of developing and implementing highly-integrated and cost-effective sensor/actuator systems that can more directly determine and respond to the actual physiological state or condition of plants or crops on a nearly real-time basis. This could enable transformational capabilities in systems “awareness”, control, and optimization of the complex dynamic interaction of plant bio-physiology and growth with the local environment (e.g., light, temperature, humidity, root zone water, nutrients, temperature, etc.) in CEA applications.

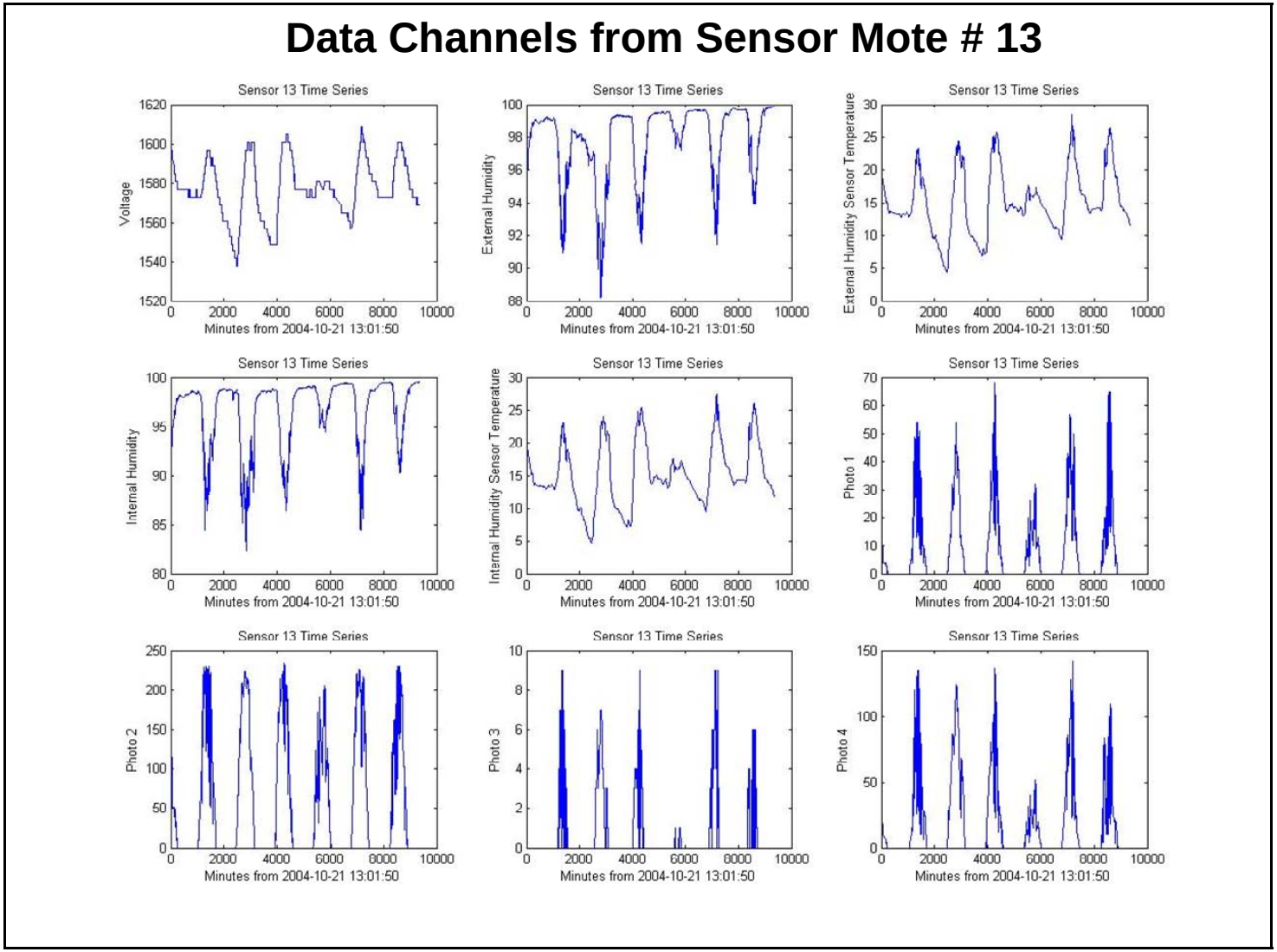

Figure 6-2 Mote data. Time varying environmental data from Sensor Mote #13 for the7-day period from October 21 to October 27. The parameters displayed are (from left to right) Top row: battery voltage, humidity sensor #1, temperature sensor #1. Middle row: humidity sensor #2, temperature sensor #2, light sensor #1. Bottom row: light sensor #2, light sensor #3, light sensor #4.

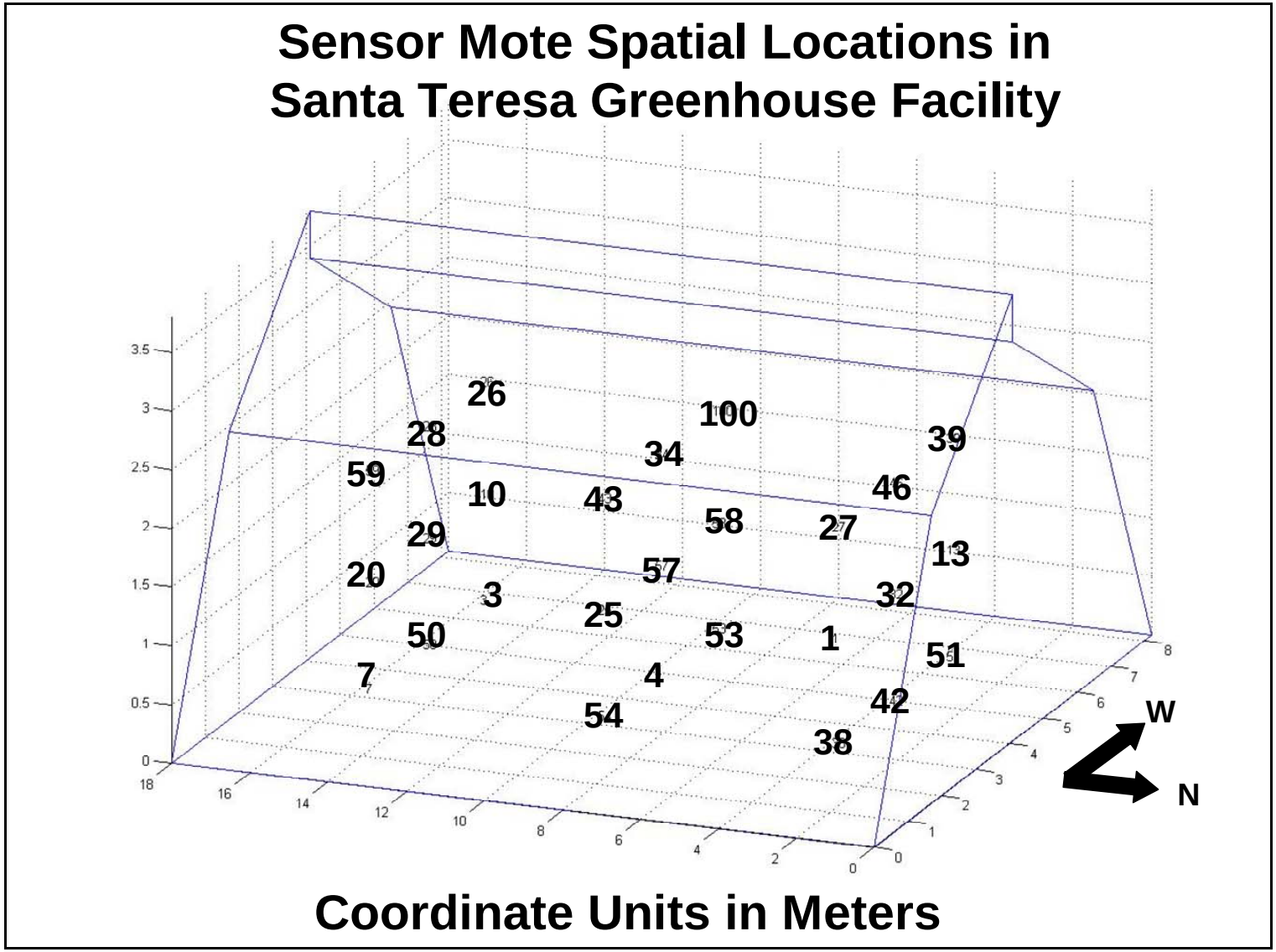

Figure 6-3 Location layout and ID #s for the 27 sensor motes hung in the three center isles in the greenhouse facility. Motes are indicated by unique ID # at their (x, y, z) locations in the greenhouse coordinate system.

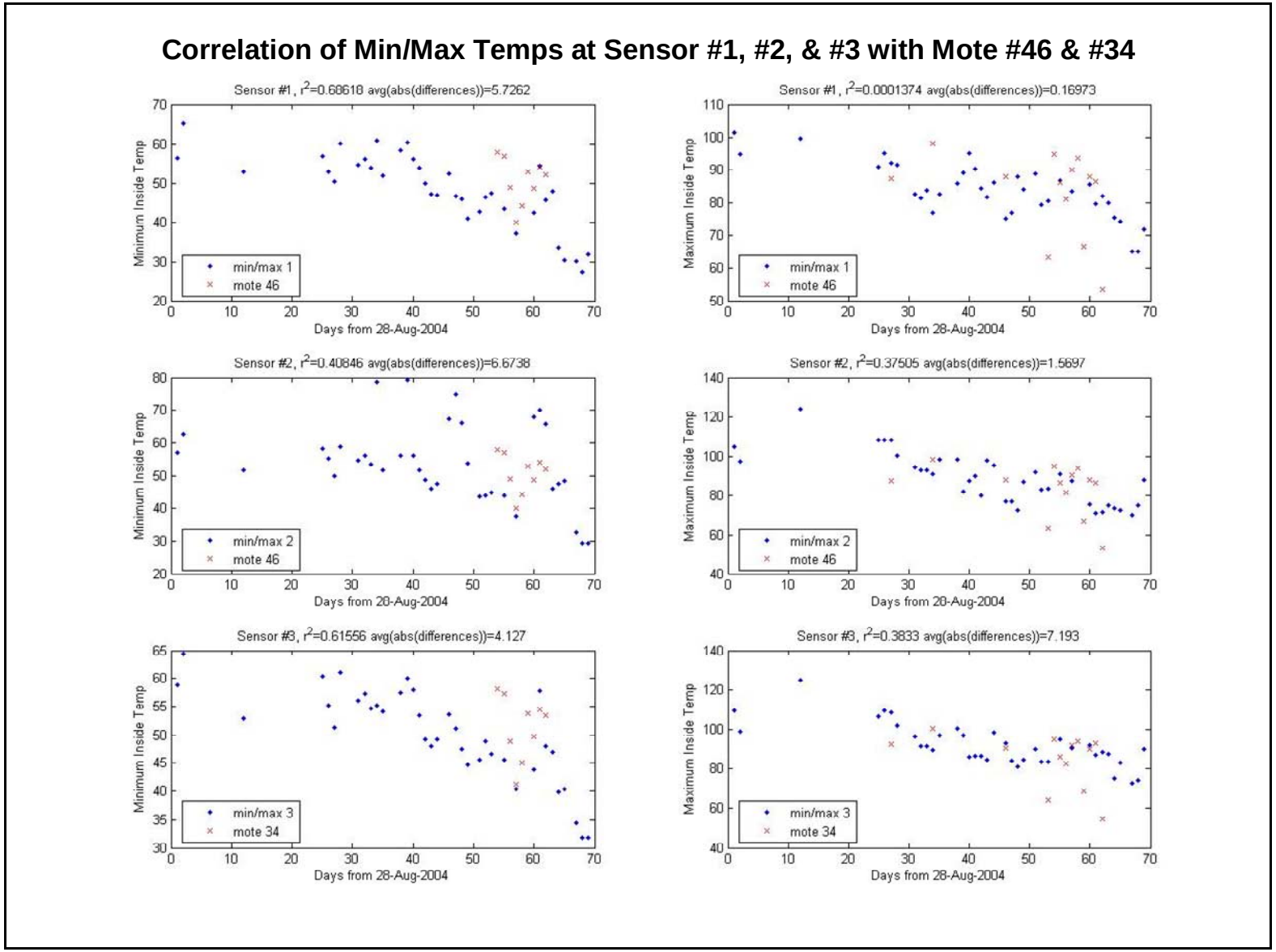

Figure 6-4 Min/max temperature data correlation between min/max sensors #1, #2, & #3 and min/max points from time series sensor motes #46 & #34.

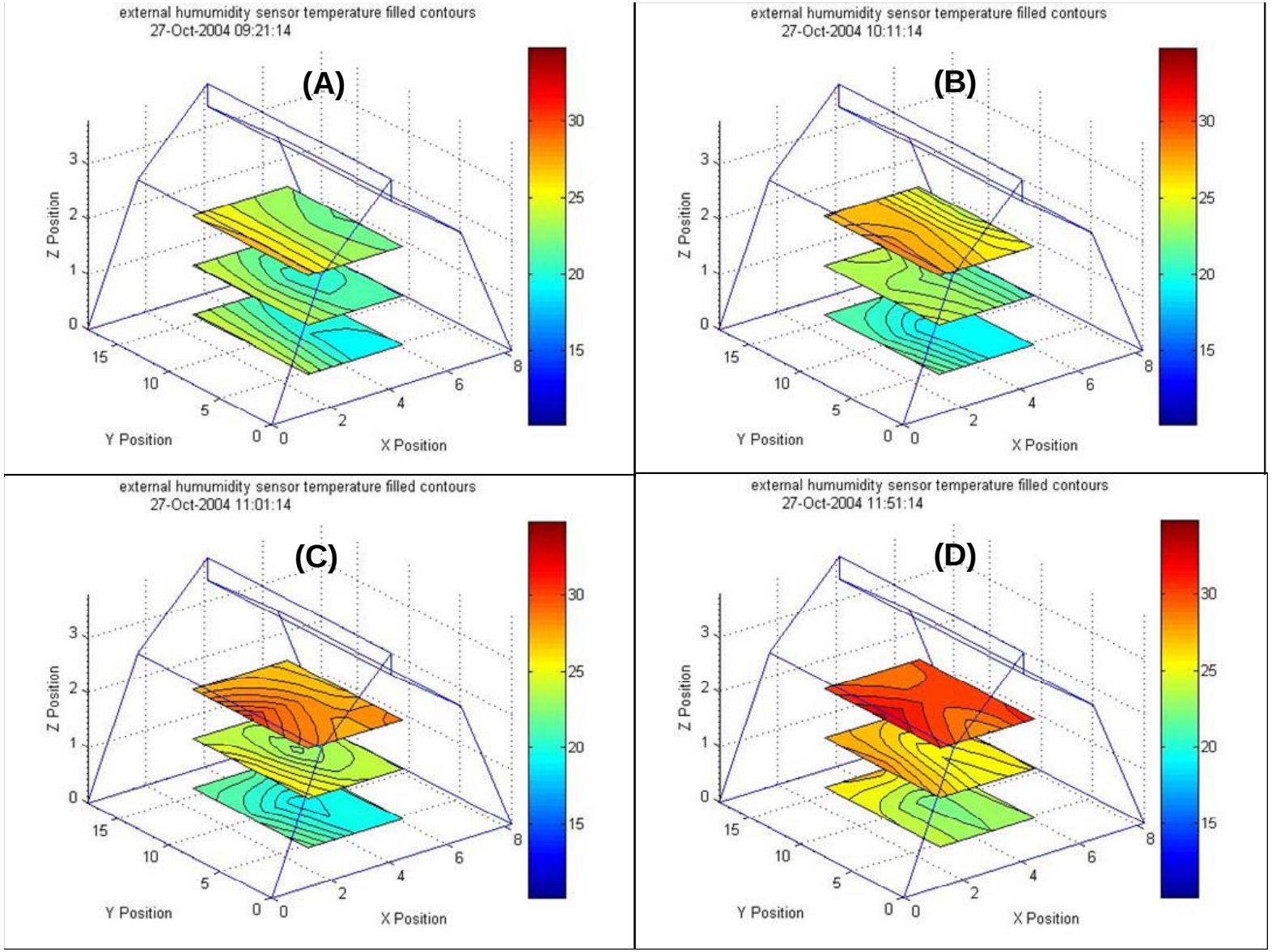

Figure 6-5 Temperature [°C] contours on planar cuts at heights above floor of z=.25m, z=1.15m, and z=1.90m at 50-minute time increments: **(A)** 9:21am, **(B)** 10:11am, **(C)** 11:01am, and **(D)** 11:51am on 27-Oct-2004.

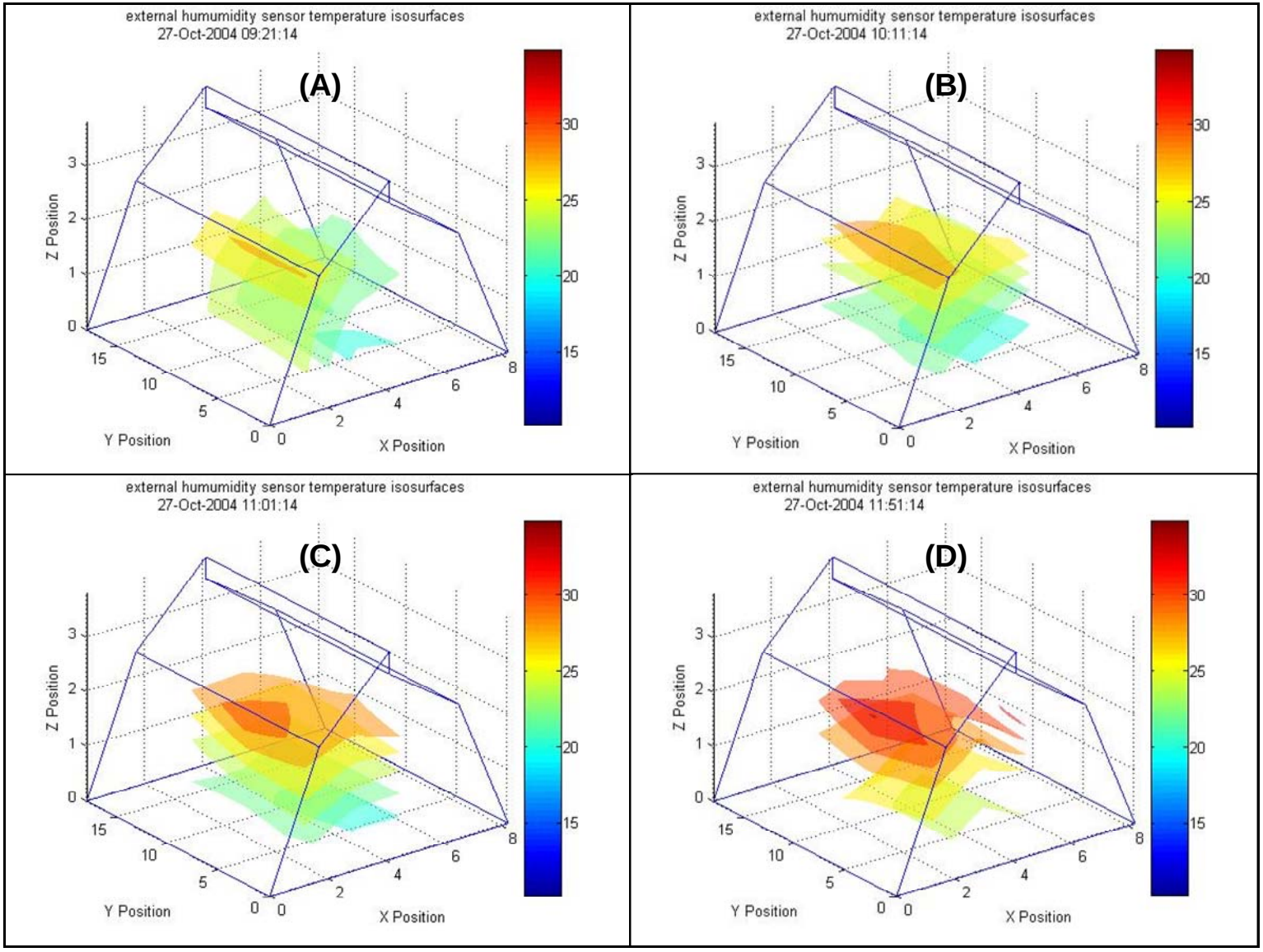

Figure 6-6 Temperature [°C] isosurfaces for 20ºC, 22ºC, 24ºC, 26ºC, 28ºC, 30ºC, and 32ºC at 50-minute time increments: **A)** 9:21am, **(B)** 10:11am, **(C)** 11:01am, and **(D)** 11:51am on 27-Oct-2004.

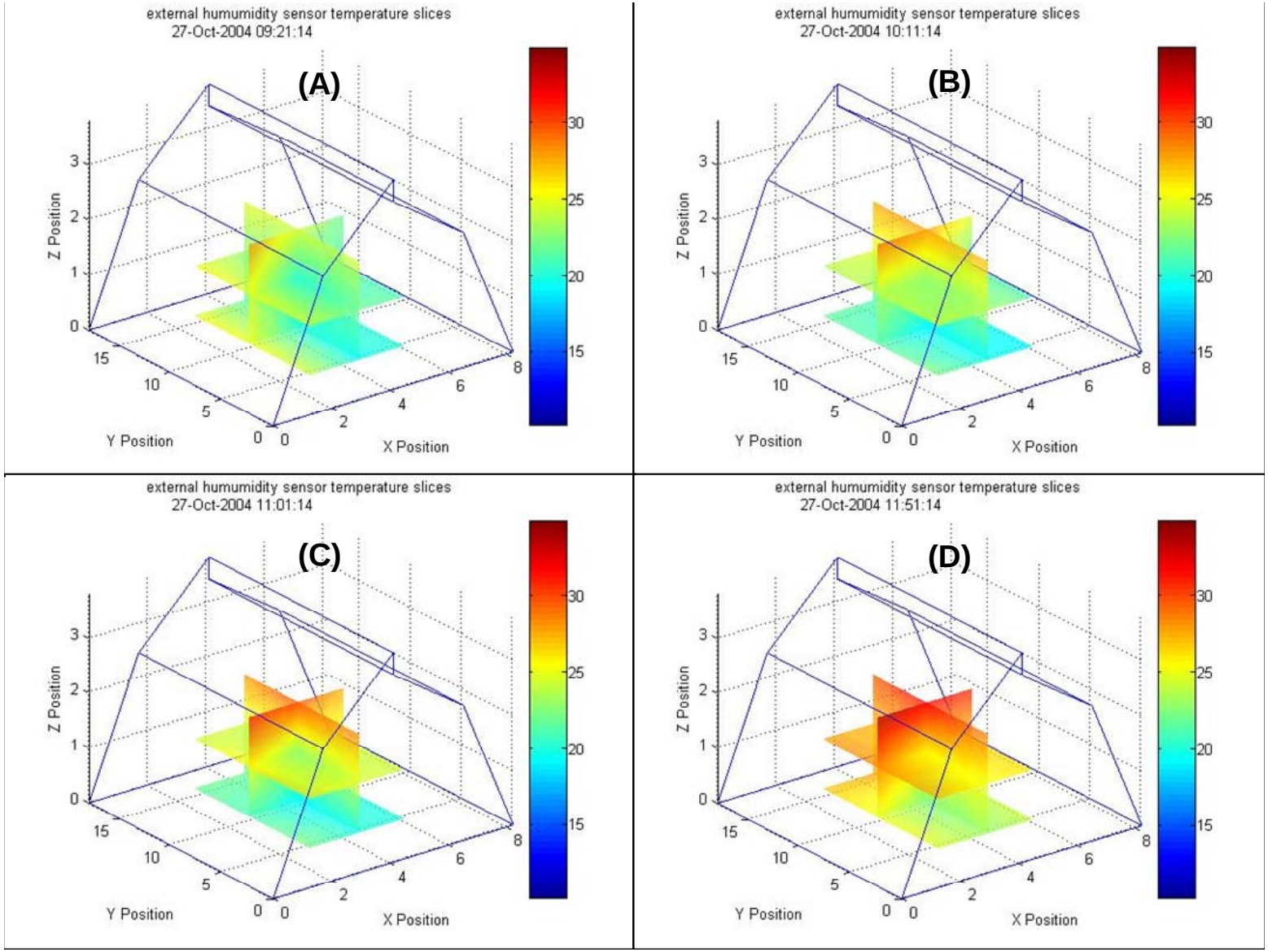

Figure 6-7 Temperature [°C] profiles in planar slices at x=4m, y=9m, z=.25m, and z=1.15m at 50-minute time increments: **(A)** 9:21am, **(B)** 10:11am, **(C)** 11:01am, and **(D)** 11:51am on 27-Oct-2004.

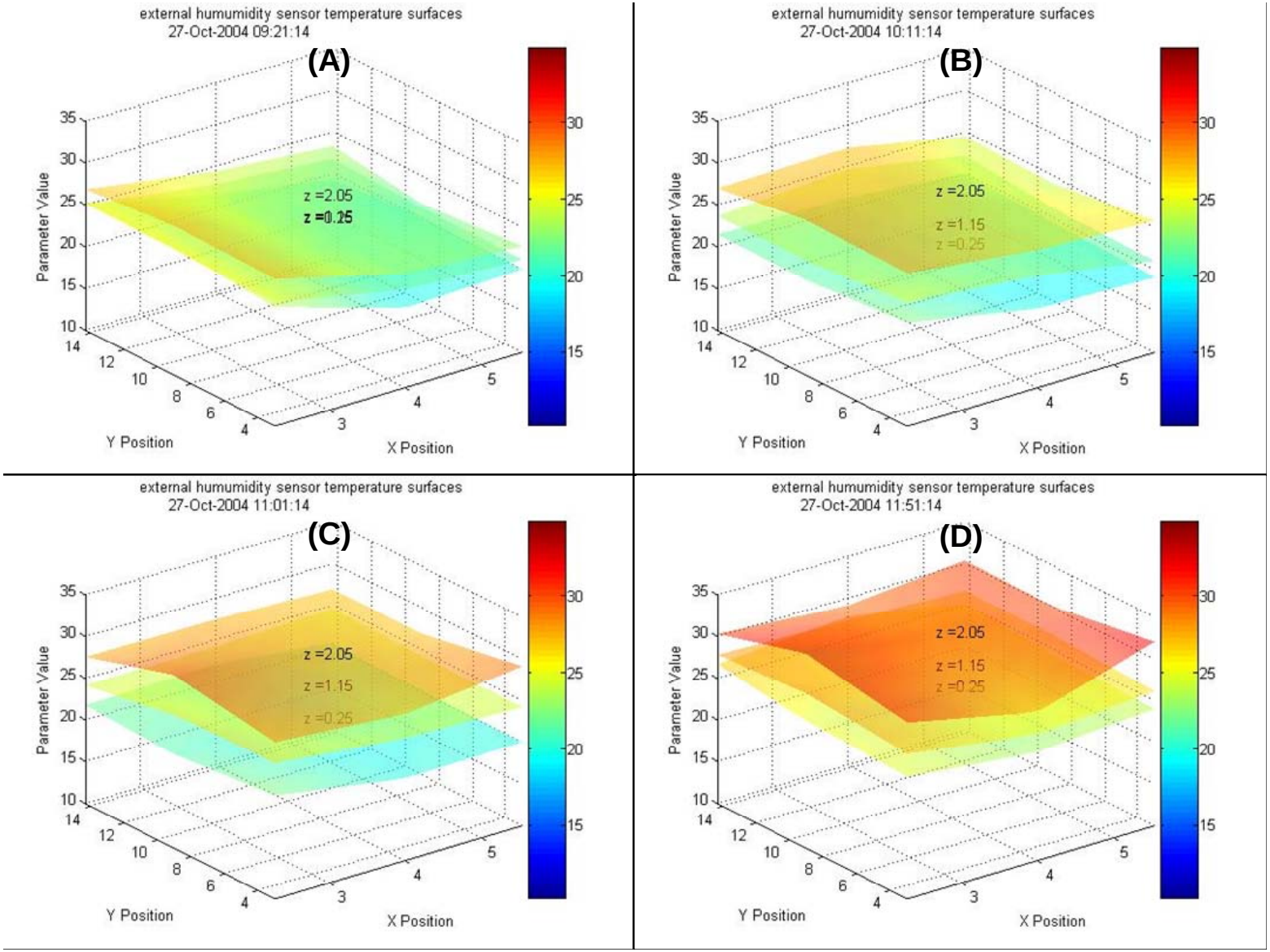

Figure 6-8 Temperature [°C] value surfaces at three different heights above floor (for z=.25m, z=1.15m, and z=2.05m) at 50-minute increments: **(A)** 9:21am, **(B)** 10:11am, **(C)** 11:01am, and **(D)** 11:51am on 27-Oct-2004.

7 Conclusions, Recommendations and Future Directions

7.1 Conclusions

Initial conclusions, based on the work accomplished to-date, are that significant water savings can be achieved with properly implemented and adjusted hydroponic forage production, but that the viability of CEA for production of relatively low-value livestock forage is likely to be much more problematic than for higher-value crops [1-2]. The cost-effectiveness of forage production will depend strongly on the availability and cost of seed, labor, and water. The water savings potential demonstrated by this project is large, with considerable room for improvement. Water use can potentially be reduced by a factor of 50 or more over open field production. The labor required to produce forage hydroponically with the system used in this project is also significant. Besides the cost of facilities and supplies, the overall viability of this approach will also depend on other factors associated with the ability of a producer to more carefully control the process and quality of the forage being produced with significantly less land and water.

The freshly harvested hydroponic forage evaluated in this project generally had good nutrition content, with the exception of calcium, and compared very well with more traditional forms of forage on a dry weight equivalent basis. The lower than desired calcium content (for cattle) would require augmentation with a calcium supplement. Further work could also be done to explore options for boosting the calcium (and other nutrient) content of the forage through use of additives to the irrigation water or edible substrate (e.g., tray) materials.

The relatively high water content of the fresh hydroponic forage dilutes its nutritional value for livestock in comparison with other less moist forms of forage, requiring that more forage be consumed by the animal to give an equivalent level of nutrition. However, the results obtained in this project were limited to the extent that time and resources precluded the investigation of further measures that could be taken to reduce the water content of the forage, perhaps through post-processing drying or the augmentation with edible tray materials that effectively increase the relative dry matter and nutrition content.

The results of this project demonstrated that hydroponic forage production can significantly reduce water consumption. It also demonstrated the ability of emerging wirelessly networked sensor (and eventually more broadly capable SDAC system) technologies hold considerable promise for embedding and distributing in CEA systems to provide improved and higher-resolution monitoring and, eventually, environmental control and enhanced operational performance.

7.2 Recommendations and Future Directions

Next steps should include conducing animal feeding and response studies with experts at NMSU to better document and evaluate the suitability of hydroponic forage for livestock. Initial target livestock of interest would be beef and dairy cattle. Additional work should include further calibrating measurement and data acquisition

instrumentation at the facility. Sensor calibration and validation in distributed networks of multi-modal sensor systems is a vexing problem that needs further work and innovation. Recommendations and approaches for implementing improved modeling and simulation of CEA systems can also be scoped and developed in collaboration with UofA CEAC personnel, with possible follow-on work that would utilize Sandia's UMBRA mod/sim framework to allow ease of code federation and the fusion and visualization of both simulated and measured data. Longer range goals still include more thorough technical and economic assessment of the performance and viability of CEA forage production as an alternative to open-field practice. Thermal management and cultivar growth tradeoffs of shade screen vs. spectrum modifying film glazing need to be further explored. Key issues for technical and economic viability include land and water usage impacts, operational economics, the nutritional suitability of the forage product as feed for a broader range of target animals, and policies associated with land use and water availability and cost. Policy and cultural acceptability issues are also important.

As costs, physical size, and power requirements of wirelessly-networked sensor systems drop, this will allow for deployment of sensors in greater numbers and densities (finer spatial resolution) and with much more flexibility (e.g., ability to quickly change or add sensor locations) and far less expense and labor than would otherwise be possible with traditional hard-wired sensors and associated data capture systems. As new and improved micro-sensor technologies emerge (including the possibility of directly sensing bio-physiological processes or key indicators of plant bio-physiological state) and more highly integrated systems are developed through the contributions of private industry, Sandia, and others, wirelessly networked SDAC systems can potentially transform the way we view and interact with our surroundings. More densely distributed sensing, combined with improved system modeling & simulation, environmental control systems, and methodologies, can be expected to provide for significant future enhancement and optimization of overall CEA system performance.

Application of wirelessly networked SDAC systems can potentially enable easily expandable and more densely distributed sensing. This opens up opportunities for much more precise real-time awareness, adaptive control, and optimization of complex dynamic interactions among various key environmental and biophysical (crop) systems. The longer-range vision for work beyond this initial project is to couple networked SDACs with improved physics-based modeling & simulation, information fusion, embedded reasoning, systems control and automation, and decision-support, to enable innovative and productive advances for CEA in general.

7.3 References

[1] Sneath, Roger, and Felicity McIntosh, "Economic evaluation of hydroponic fodder for a small cattle enterprise", DPI&F Note, Department of Primary Industries and Fisheries, Queensland Government, Australia [http://dpi.qld.gov.au/beef/14774.html].

[2] Sneath, Roger, and Felicity McIntosh, "Hydroponic fodder for beef cattle: Beware the cost", DPI&F Note, Department of Primary Industries and Fisheries, Queensland Government, Australia [http://dpi.qld.gov.au/beef/14720.html].

8 Appendices

8.1 Appendix A: Daily Operations Log Sheet

Santa Teresa Hydroponic Greenhouse Forage Project Operations
Daily Operations Data Sheet

Date:_____ Operations Start Time:_____

Operator Name(s):_____

Step-1: Daily Environmental Data Collection

Station 1 Current Temp & RH
Temp [°F] In:_____Out:___
RH [%]:_____
*Station 1 Read-Reset time:*_____

Station 1 Min/Max Temp & RH
Temp In Min:_____Max:_____
Temp Out Min:_____Max:_____
RH [%] Min:_____Max:_____

Station 2 Current Temp & RH
Temp [°F] In:_____Out:___
RH [%]:_____
*Station 2 Read-Reset time:*_____

Station 2 Min/Max Temp & RH
Temp In Min:_____Max:_____
Temp Out Min:_____Max:_____
RH [%] Min:_____Max:_____

Station 3 Current Temp & RH
Temp [°F] In:_____Out:___
RH [%]:_____
*Station 3 Read-Reset time:*_____

Station 3 Min/Max Temp & RH
Temp In Min:_____Max:_____
Temp Out Min:_____Max:_____
RH [%] Min:_____Max:_____

Station 4 Current Temp & RH
Temp [°F] In:_____Out:___
RH [%]:_____
*Station 4 Read-Reset time:*_____

Station 4 Min/Max Temp & RH
Temp In Min:_____Max:_____
Temp Out Min:_____Max:_____
RH [%] Min:_____Max:_____

Station 5 Current Temp & RH
Temp [°F] In:_____Out:___
RH [%]:_____
*Station 5 Read-Reset time:*_____

Station 5 Min/Max Temp & RH
Temp In Min:_____Max:_____
Temp Out Min:_____Max:_____
RH [%] Min:_____Max:_____

Station 6 Current Temp & RH
Temp [°F] In:_____Out:___
RH [%]:_____
*Station 6 Read-Reset time:*_____

Station 6 Min/Max Temp & RH
Temp In Min:_____Max:_____
Temp Out Min:_____Max:_____
RH [%] Min:_____Max:_____

Irrigation Water Meter Reading [Gallons]:_____ Time of Reading:_____

Step-2: Forage Harvest Operations

Harvest Operations Start Time:_____ Harvest Ops End Time:_____

Crop Type	Number of Harvested Trays in Weighed Load / Weight [Lbs] per Load							
	Load 1	**Load 2**	**Load 3**	**Load 4**	**Load 5**	**Load 6**	**Load 7**	**Load 8**
Barley								
Barley Harvest Start Time:							*End Time:*	
Corn								
Corn Harvest Start Time:							*End Time:*	
Oats								
Oat Harvest Start Time:							*End Time:*	
Sorghum								
Sorghum Harvest Start Time:							*End Time:*	
Triticale								
Triticale Harvest Start Time:							*End Time:*	
Wheat								
Wheat Harvest Start Time:							*End Time:*	

Step-3: Tray Wash and Disinfection Tank Preparation

Wash Tank… Initial / Final Water Meter Readings [Gal]: _____ Soap [ml]:_____

Rinse Tank… Initial / Final Water Meter Readings [Gal]:_____ Bleach [ml]:_____

Step-4: Tray Cleaning, Re-Seeding, and Racking Operations

Crop Type	**# of Trays Cleaned/Reseeded/Racked**	Ops Start Time	**Ops End Time**
Barley			
Corn			
Oats			
Sorghum			
Triticale			
Wheat			

Step-5 Seed Preparation… Measurement, Wash, Disinfect-Soak, and Drain Operations

Seed Wash and Soak Operations Start Time:_____ End Time:_____

Wash Tank… Initial / Final Water Meter Readings [Gal]: _____

Soak Tank… Initial / Final Water Meter Readings [Gal]:_____ Bleach [ml]:_____

Crop Type	**Dry Weight of Seed Used [lbs]**	
	Bucket-1	**Bucket-2**
Barley		
Corn		
Oats		
Sorghum		
Triticale		
Wheat		

Manual Soak Tank Drain Operation (Yes/No):_____ Started at Time:_____

Automatic Timer Tank Drain Operation (Yes/No):__ Set to Begin at Time:_____

Step-6: Operations Wrap-Up Check List & Comments

_____Pick-up Area and Bag Trash _____Stow Equipment

_____Close GH Doors _____Close Water Meter Housing Lids

_____Close & Lock Storage Container

Other Comments, Observations, and/or Problems Needing to be Addressed:

_____

Operator Signature(s) Date Time

8.2 Appendix B: Mold Diagnostic Report

Sample #: **0400246**
Host:Wheat
Received: 8/24/2004
County: Dona Ana
Field ID: Hydroponic Forage Greenhouse
NPDN-920-77540
NMSU Plant Diagnostic Clinic
Box 30003, MSC 3AE
Las Cruces NM 88003
Tel: (505) 646-1965
Fax: (505) 646-8085
Federal Tax ID#: 01-507888-

Client and Submitter: [Sandia National Lab Dept. 4148]
Ed Baynes
NM
Tel: 505-681-0502
Fax:
Mobile: 505-527-5005

Diagnosis and Recommendation:

Host/Habitat Wheat (Triticum)
Diagnosis/ID Bipolaris (Bipolaris)
Diagnosis/ID Fusarium root rot (Fusarium)
Diagnosis/ID Rhizopus (Rhizopus)

Rhizopus stolonifer ("bread mold") was growing abundantly on all of the samples submitted. This fungus is common on decaying plant material. It can be a "post-harvest" pathogen on many fruit and vegetable crops. On wheat, it is part of a complex of different fungi that cause "kernel smudge or black point" on newly harvested grain. It is not a particularly good competitor in soil environments. As such it is rarely associated with seedling diseases. However, it can attack seed when competition is reduced or eliminated; such as hydroponic culture. This fungus is likely contributing to the over decay that is occurring. Two more common wheat pathogens were also isolated from the sample submitted: *Fusarium* sp. and *Bipolaris sorokiniana.* These two pathogens together cause several diseases on wheat. They cause a disease called "common root and foot rot." They can also cause leaf spot diseases and seedling diseases. In addition to the seedling disease in the sample submitted, we were able to find a number of leaf spots as well. Although these fungi do well in dry conditions in the field, they obviously do very well in wet environments as well. When pathogens get into a hydroponic situation, they can behave somewhat different then they do in fields. All three of these organisms are ubiquitous in the environment. They are good saprophytes as well as pathogens and can survive without a host plant almost indefinetly.

Likely sources of these organisms include seed, soil, plant debris and water (depending on source). Since you clean your seed and your flats before use, water is probably the first source to consider. Because you are growing this wheat for feed, I am not sure what would be safe to use as far as a treatment. There are several "disinfectants" which are used in greenhouses to help prevent disease and algae growth. These materials are generally safe for humans (though I wouldn't drink them!). Sanitation is going to be a key in managing these problems. In addition to cleaning seed and flats, removal of infected flats is recommended.

Natalie Goldberg, For NMSU Plant Diagnostic Clinic Completed Date: 8/29/2004

8.3 Appendix C: Wireless sensor mote data

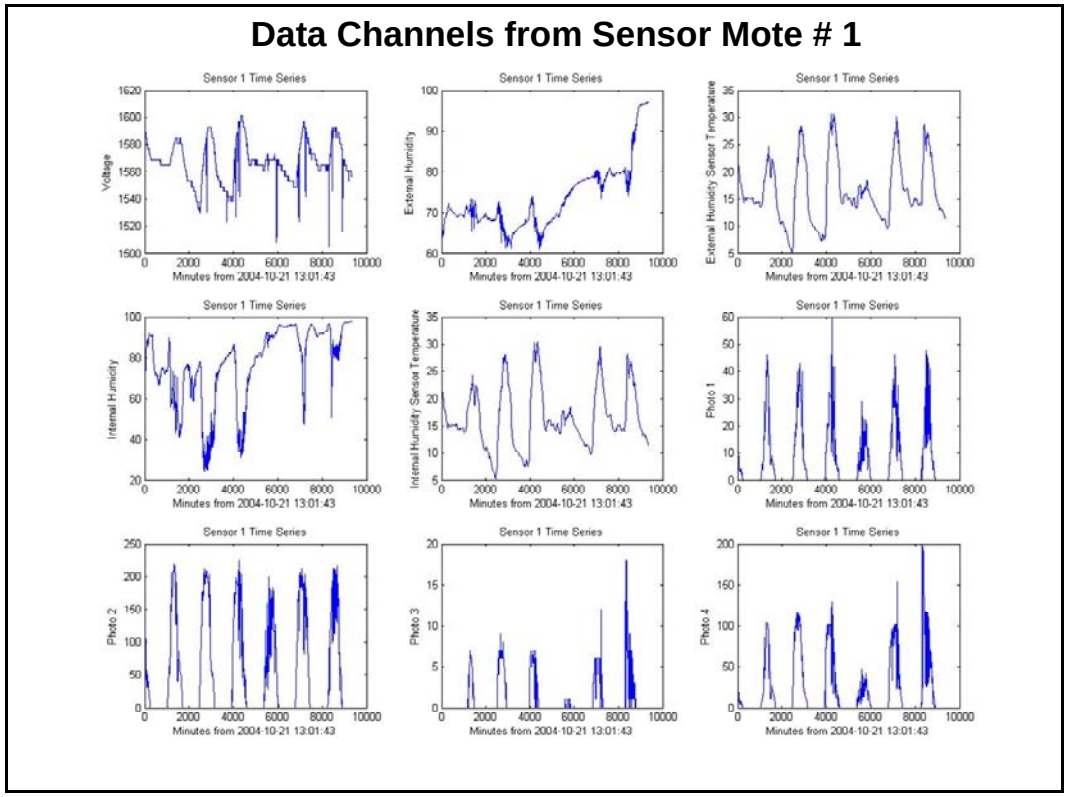

Figure 8-1 Data from Mote #1 for the period October 21-27, 2004.

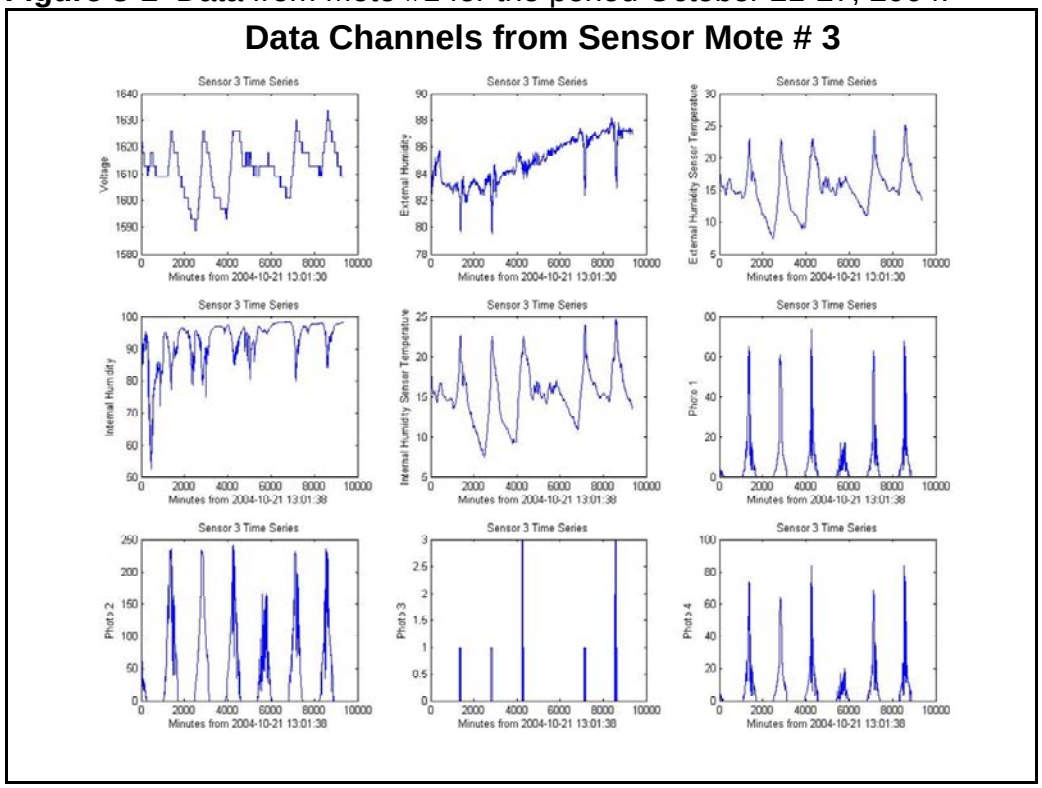

Figure 8-2 Data from Mote # 3 for the period October 21-27, 2004.

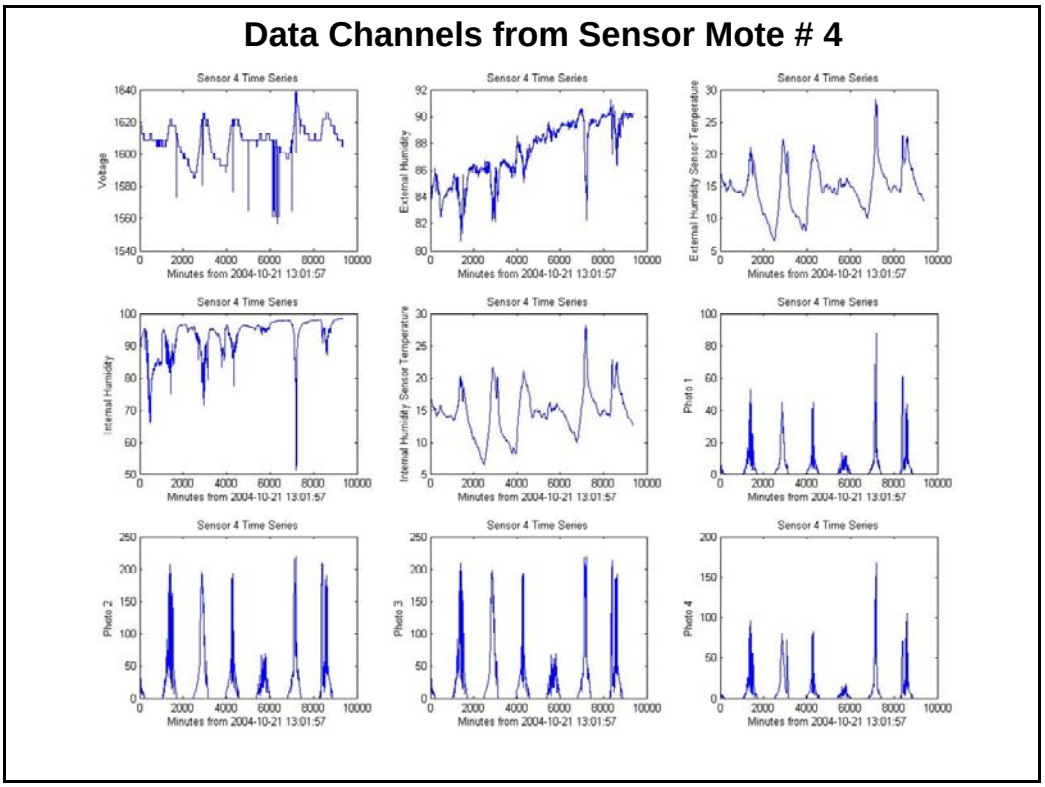

Figure 8-3 Data from Mote # 4 for the period October 21-27, 2004.

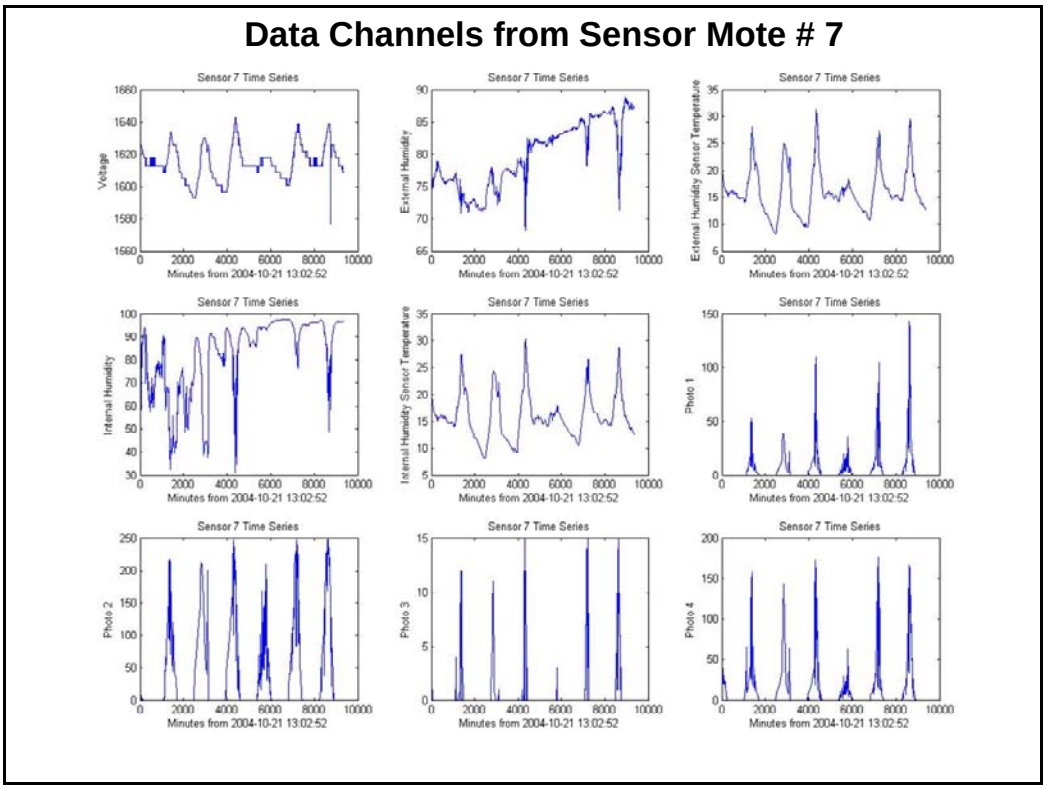

Figure 8-4 Data from Mote # 7 for the period October 21-27, 2004.

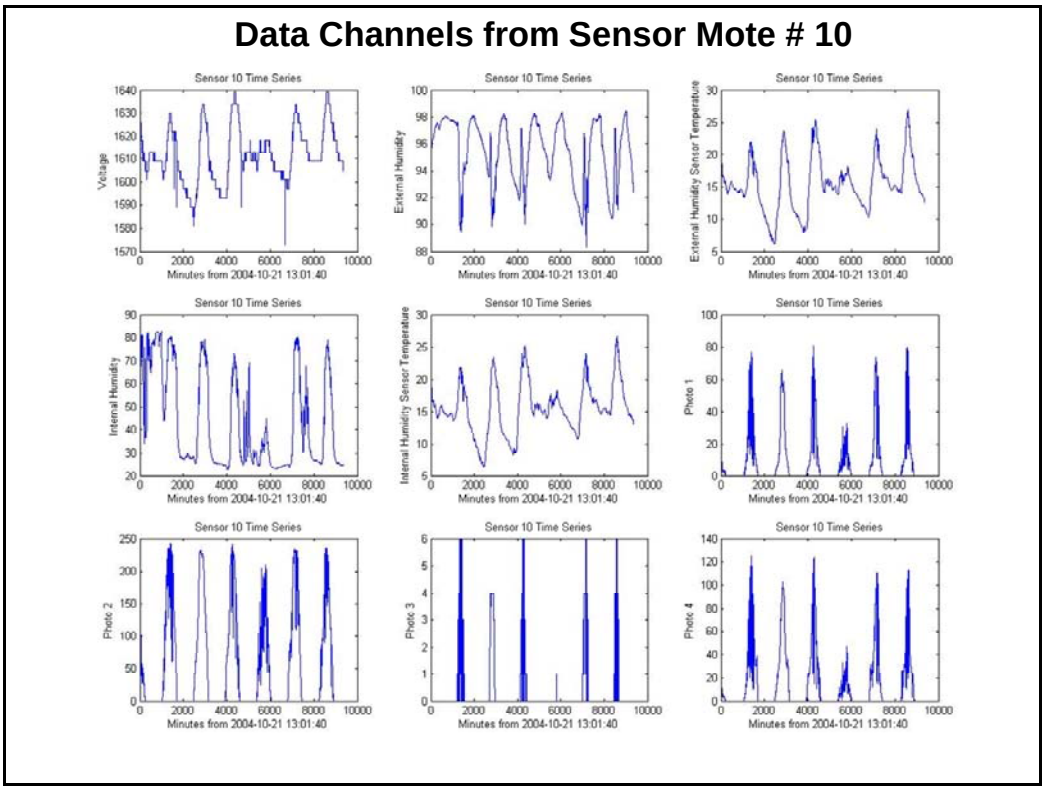

Figure 8-5 Data from Mote # 10 for the period October 21-27, 2004.

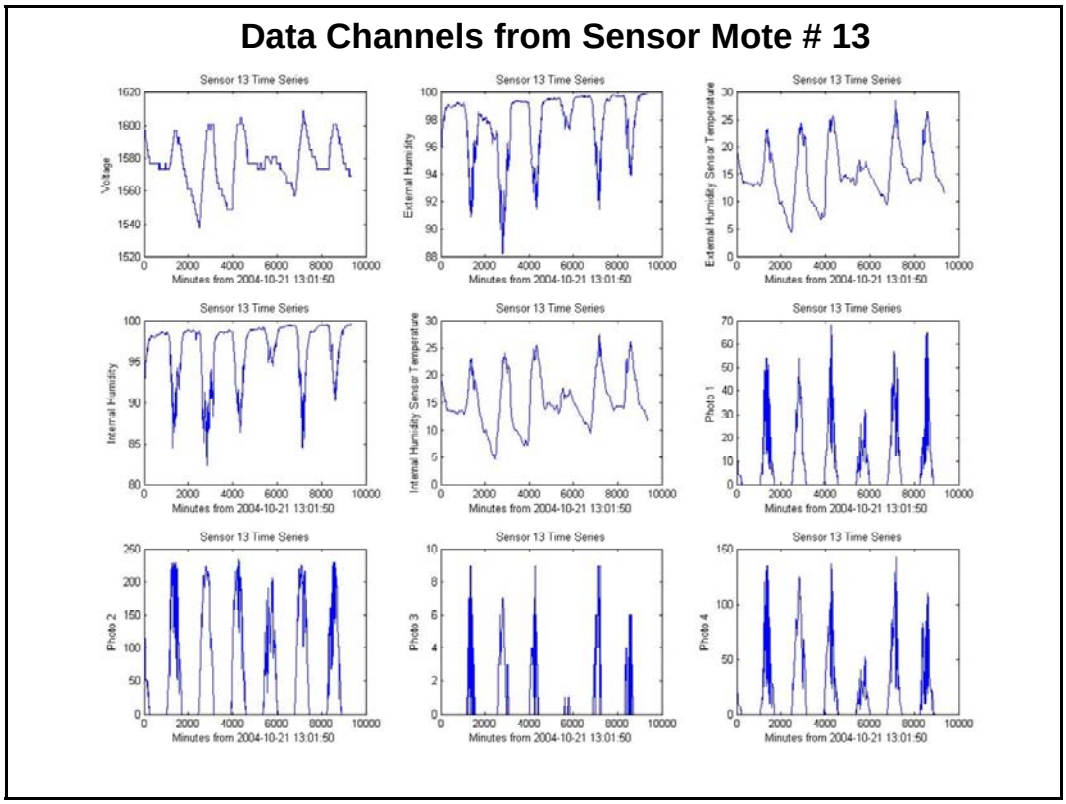

Figure 8-6 Data from Mote # 13 for the period October 21-27, 2004.

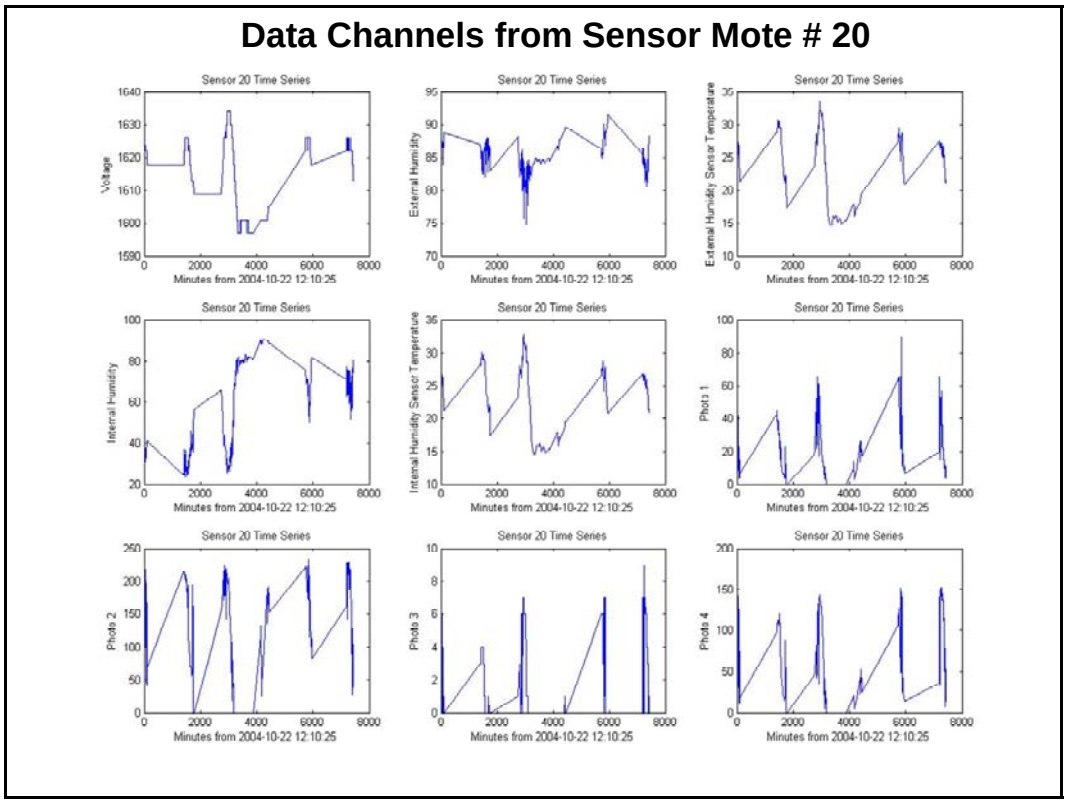

Figure 8-7 Data from Mote # 20 for the period October 21-27, 2004.

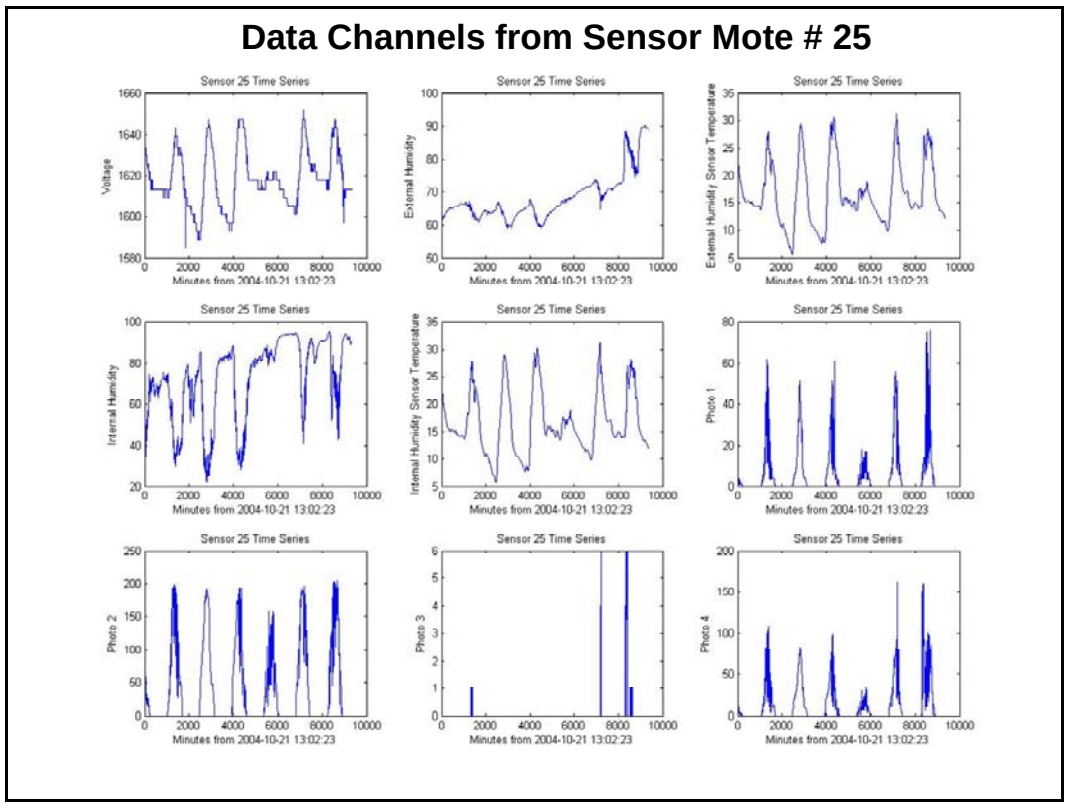

Figure 8-8 Data from Mote # 25 for the period October 21-27, 2004.

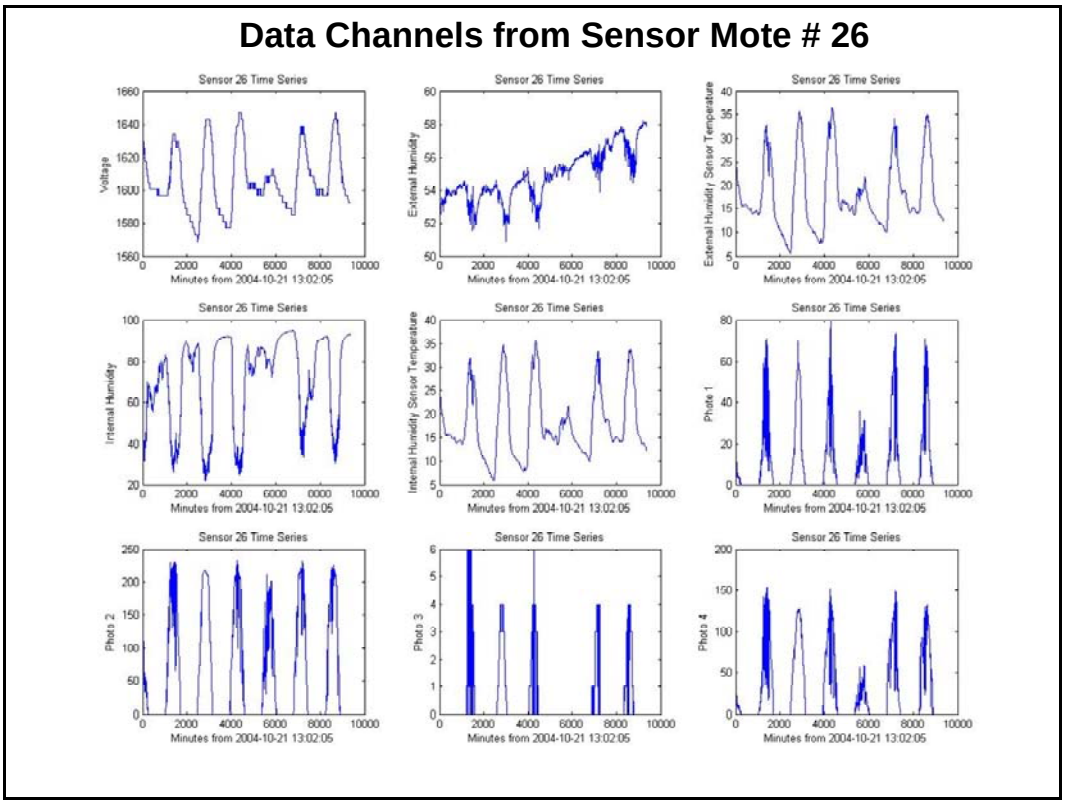

Figure 8-9 Data from Mote # 26 for the period October 21-27, 2004.

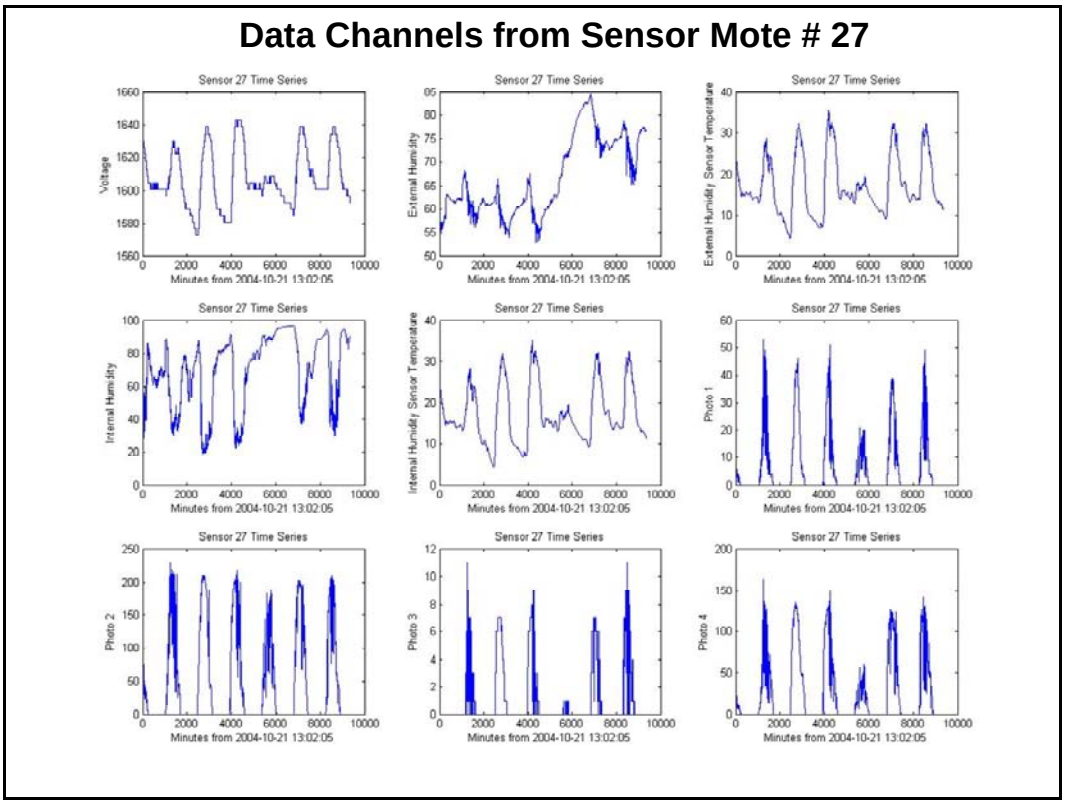

Figure 8-10 Data from Mote # 27 for the period October 21-27, 2004.

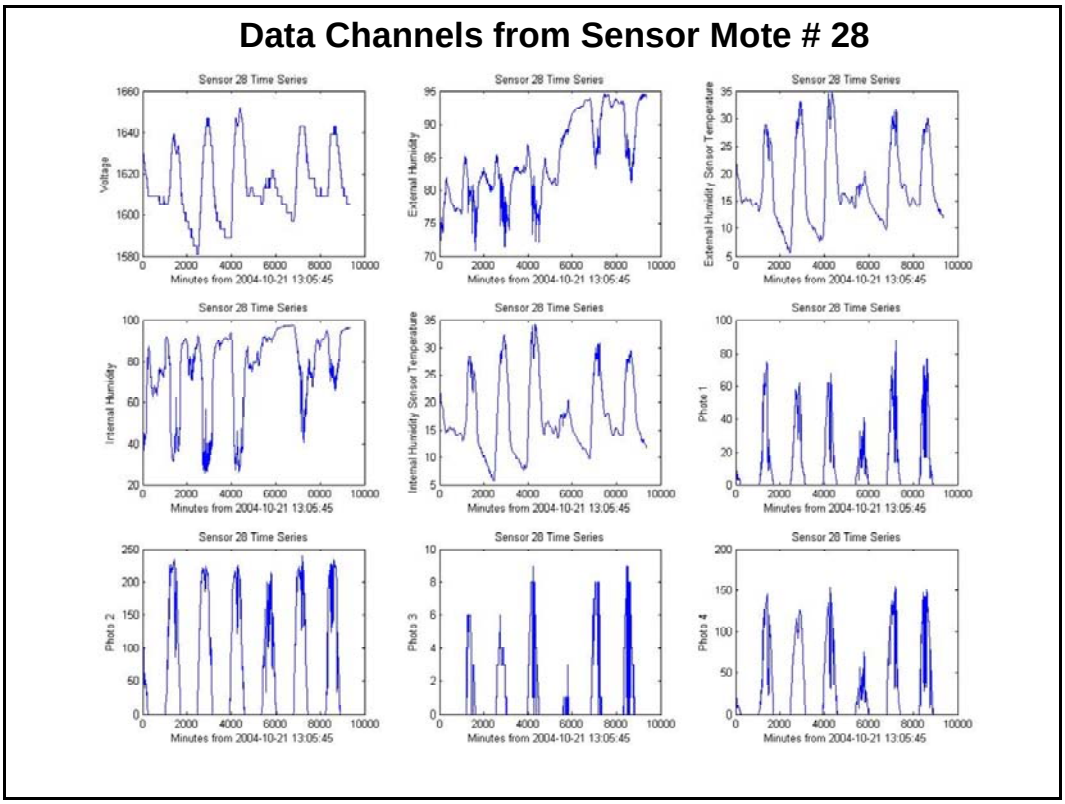

Figure 8-11 Data from Mote # 28 for the period October 21-27, 2004.

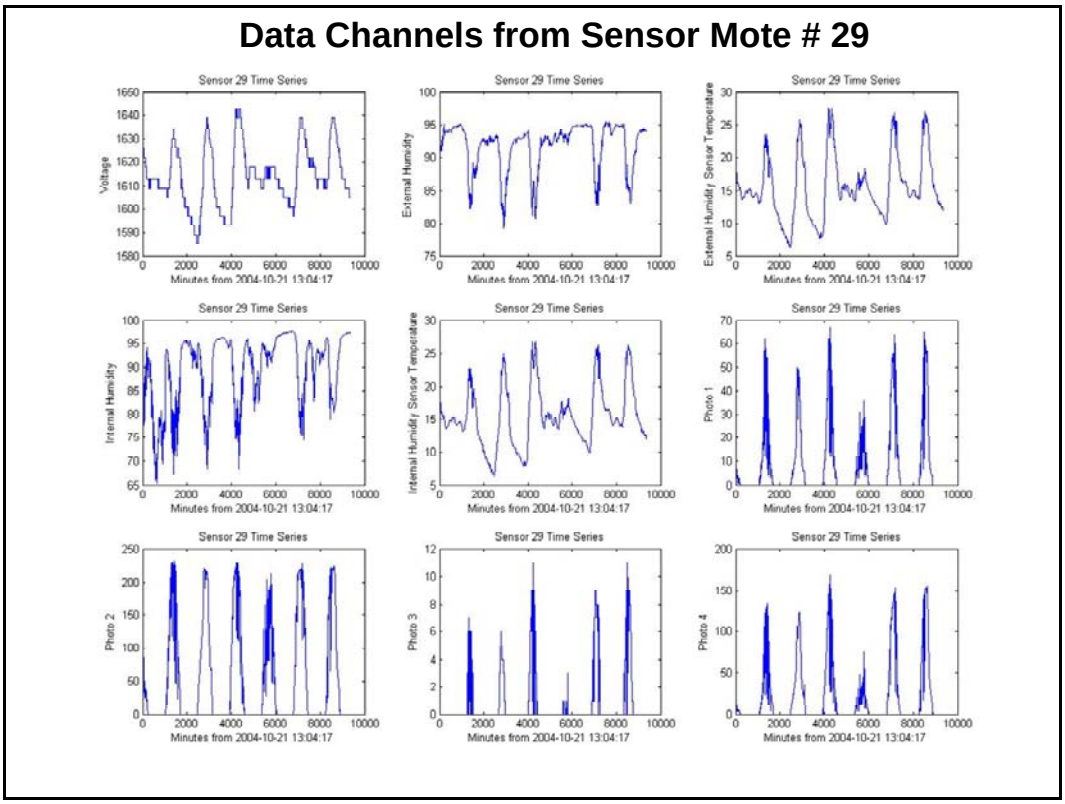

Figure 8-12 Data from Mote # 29 for the period October 21-27, 2004.

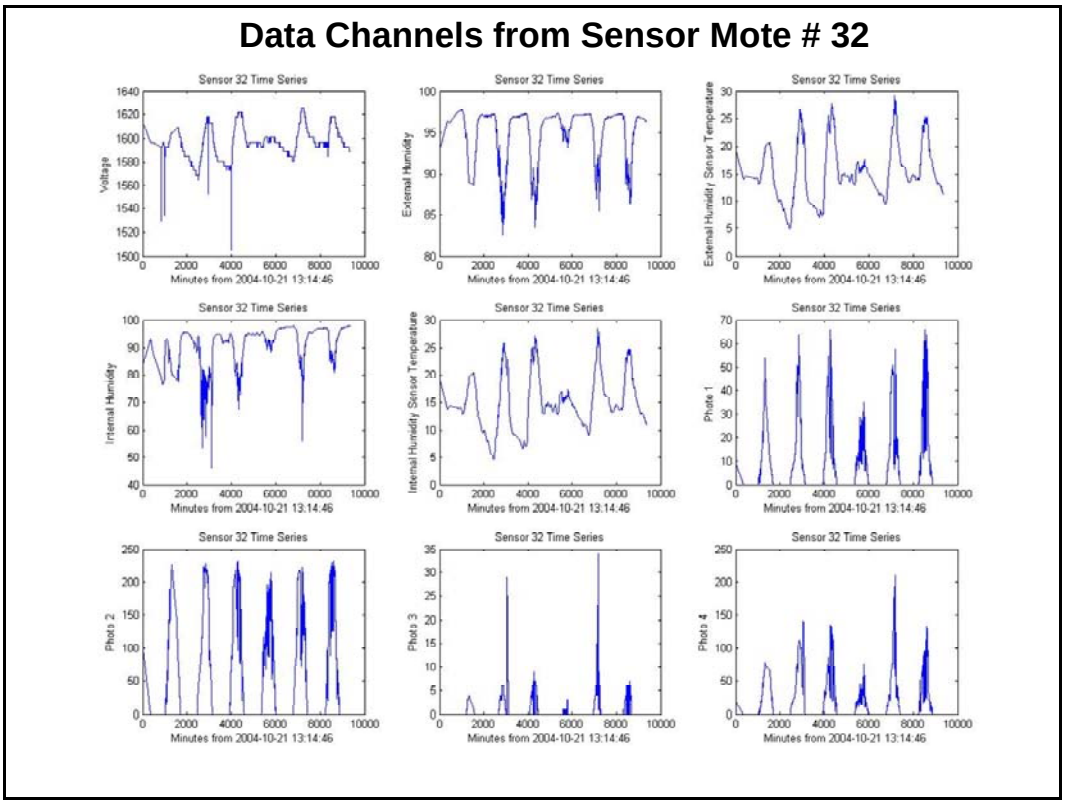

Figure 8-13 Data from Mote # 32 for the period October 21-27, 2004.

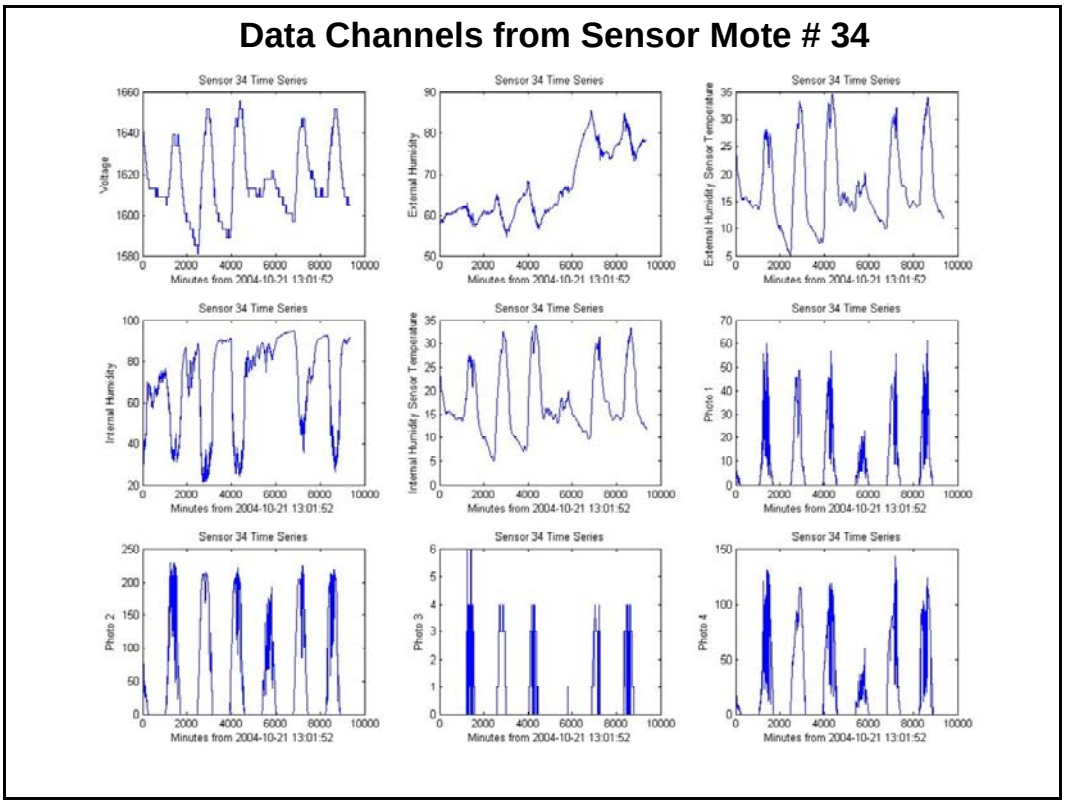

Figure 8-14 Data from Mote # 34 for the period October 21-27, 2004.

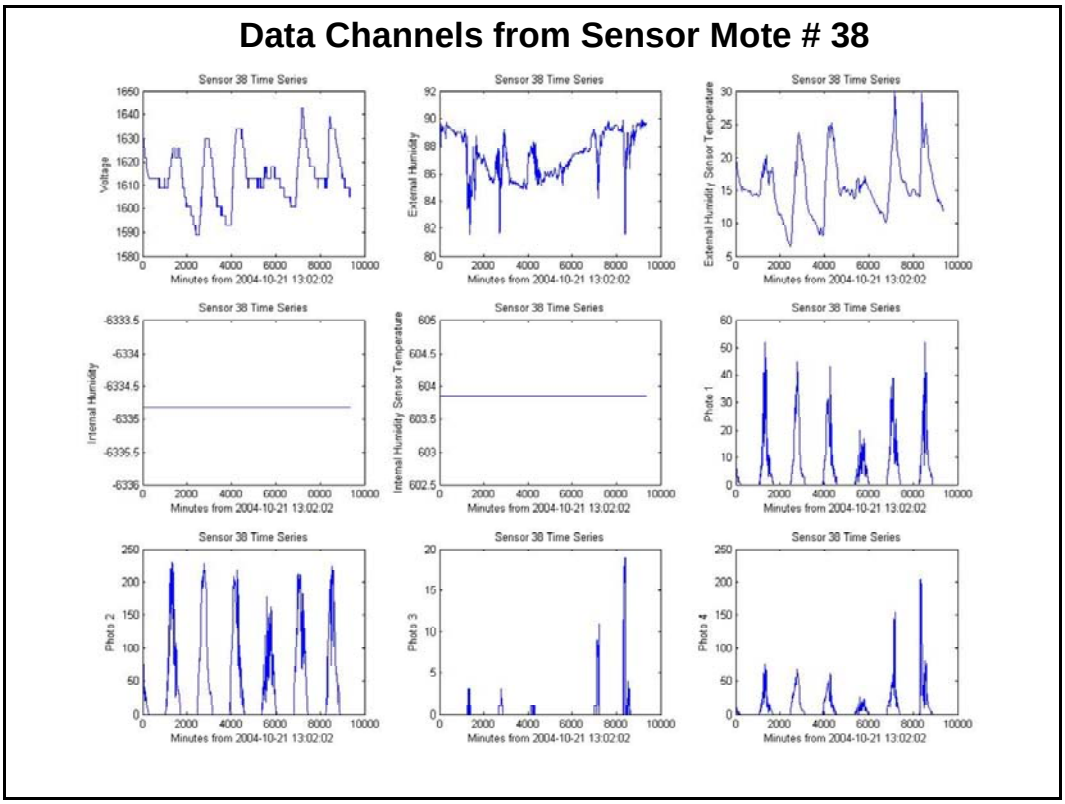

Figure 8-15 Data from Mote # 38 for the period October 21-27, 2004.

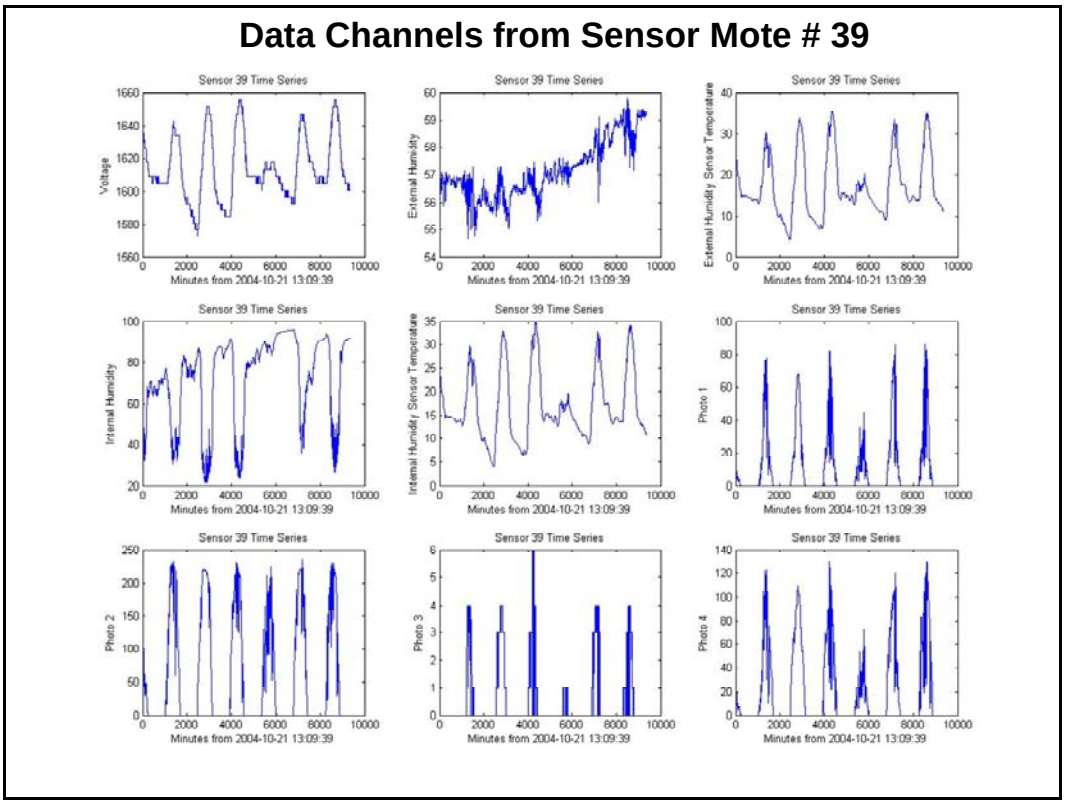

Figure 8-16 Data from Mote # 39 for the period October 21-27, 2004.

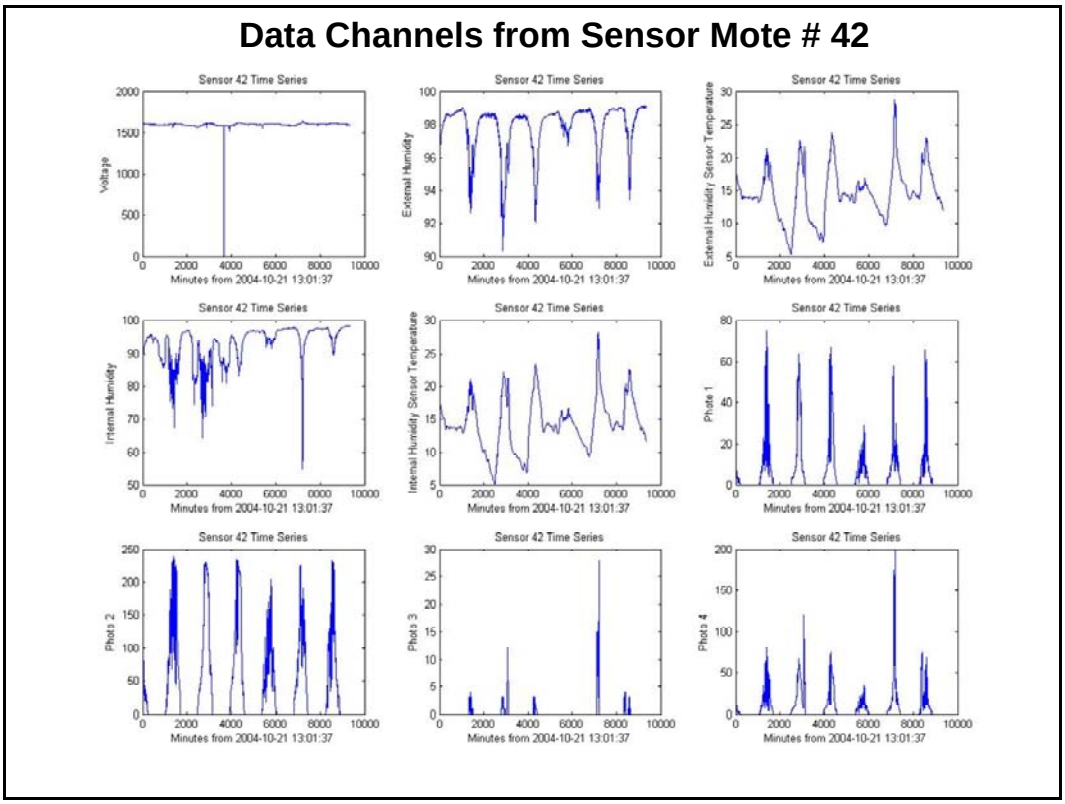

Figure 8-17 Data from Mote # 42 for the period October 21-27, 2004.

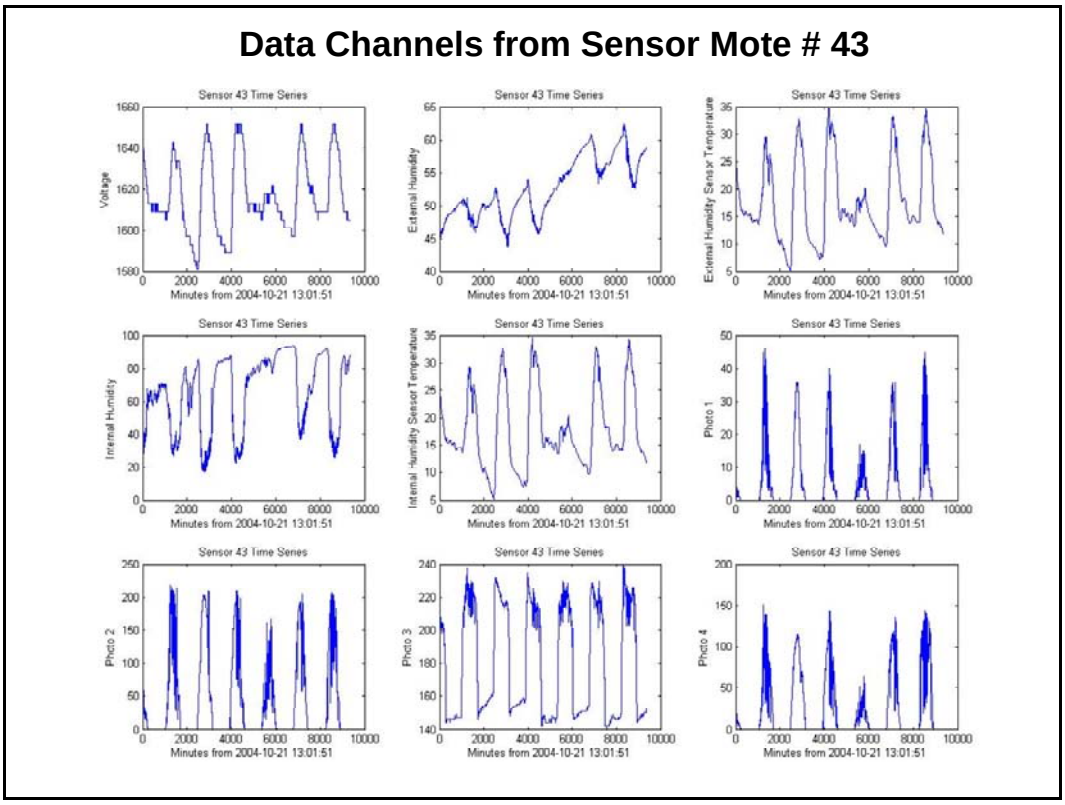

Figure 8-18 Data from Mote # 43 for the period October 21-27, 2004.

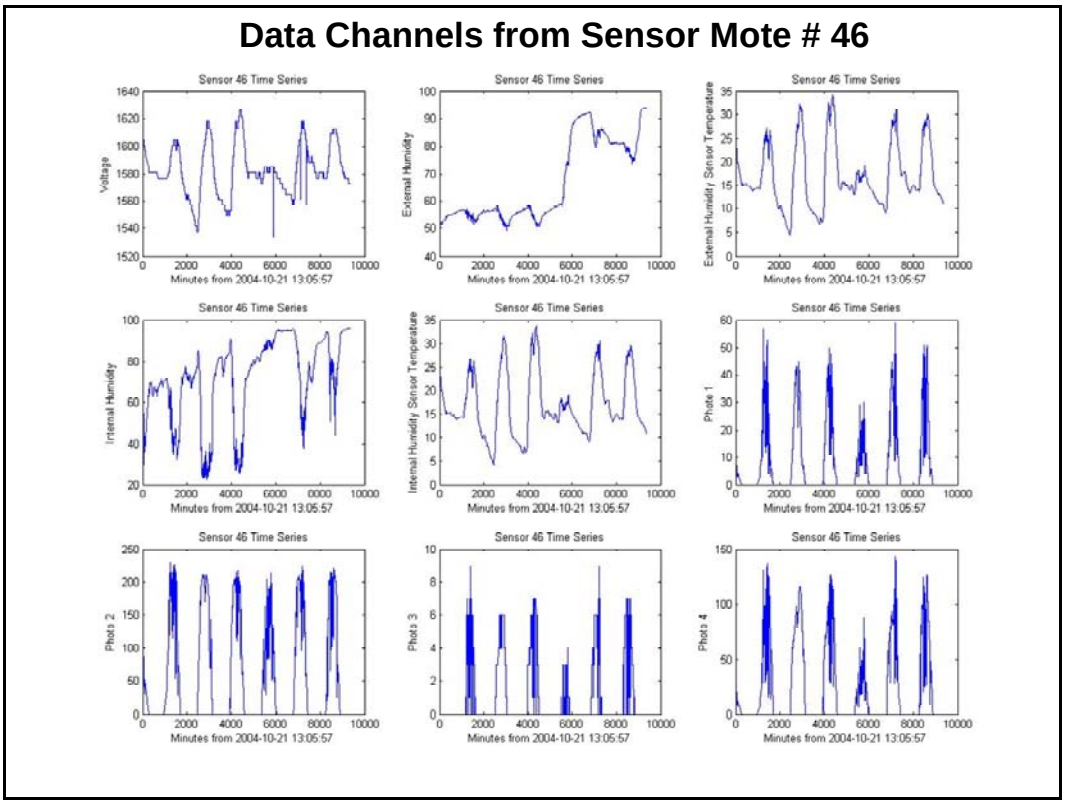

Figure 8-19 Data from Mote # 46 for the period October 21-27, 2004.

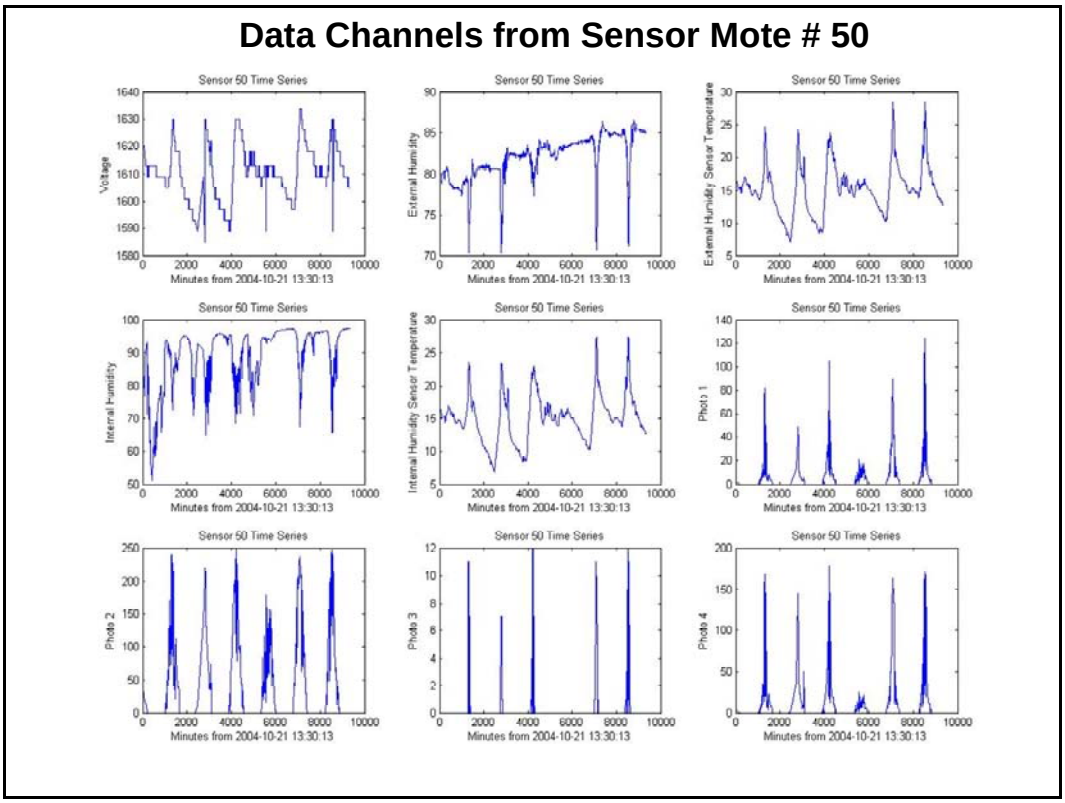

Figure 8-20 Data from Mote # 50 for the period October 21-27, 2004.

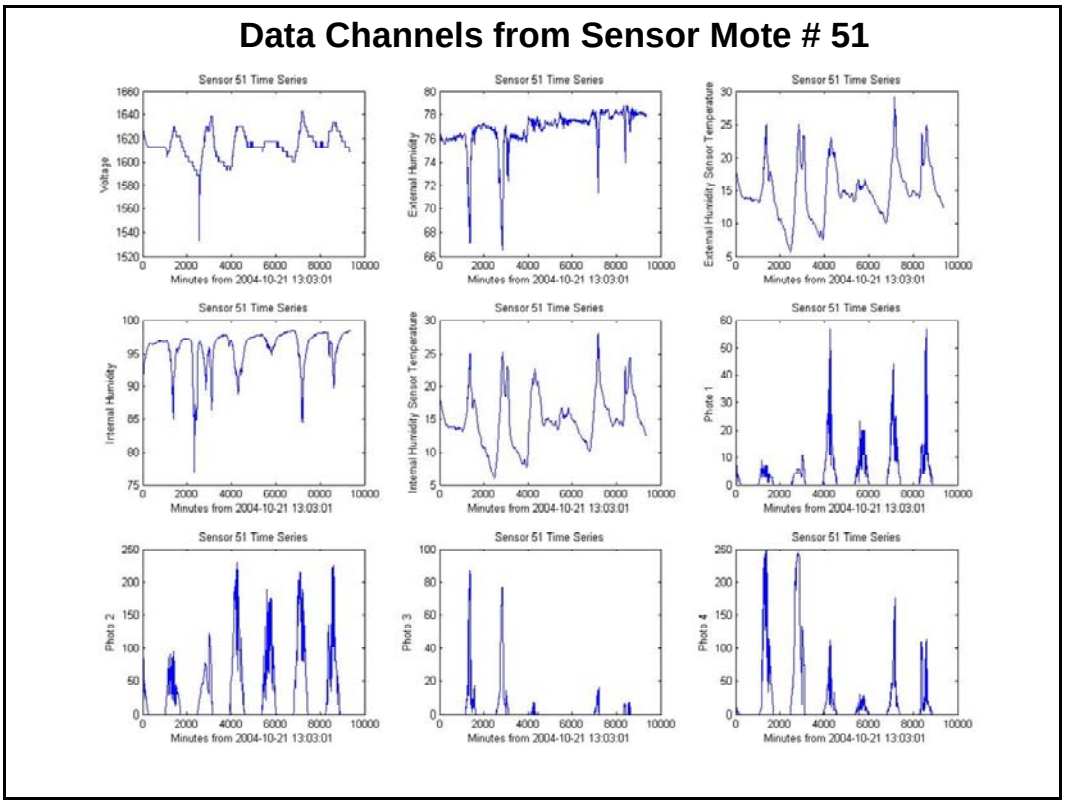

Figure 8-21 Data from Mote # 51 for the period October 21-27, 2004.

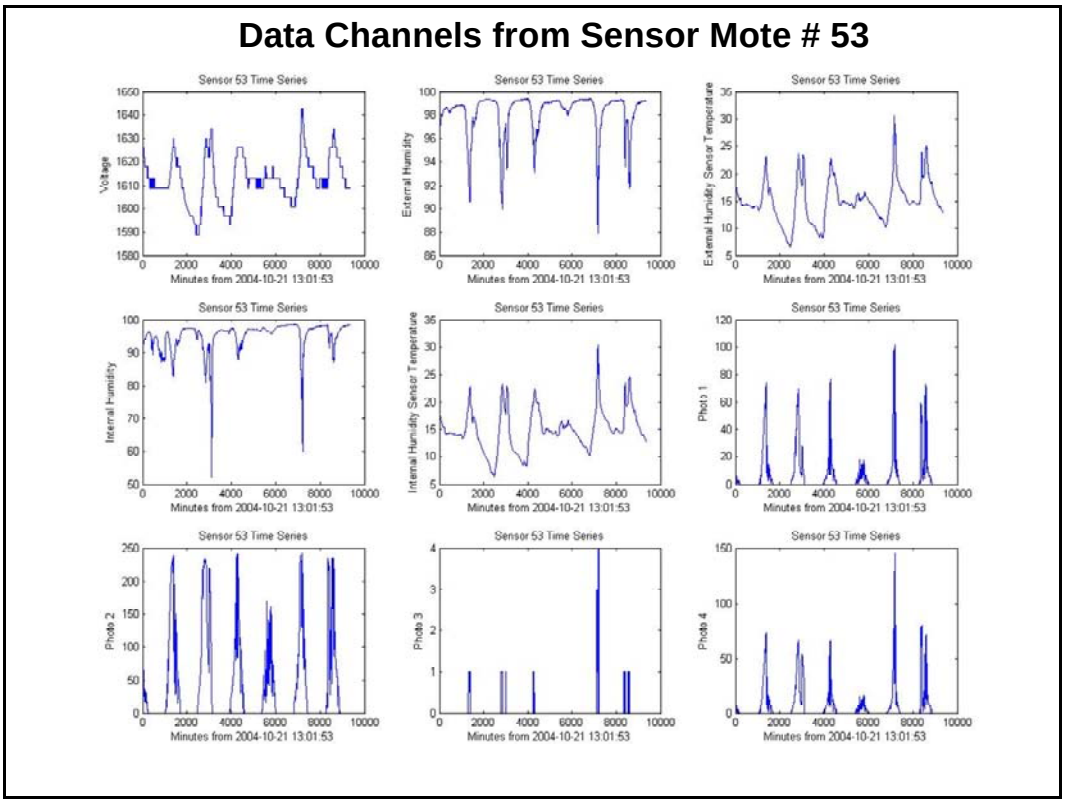

Figure 8-22 Data from Mote # 53 for the period October 21-27, 2004.

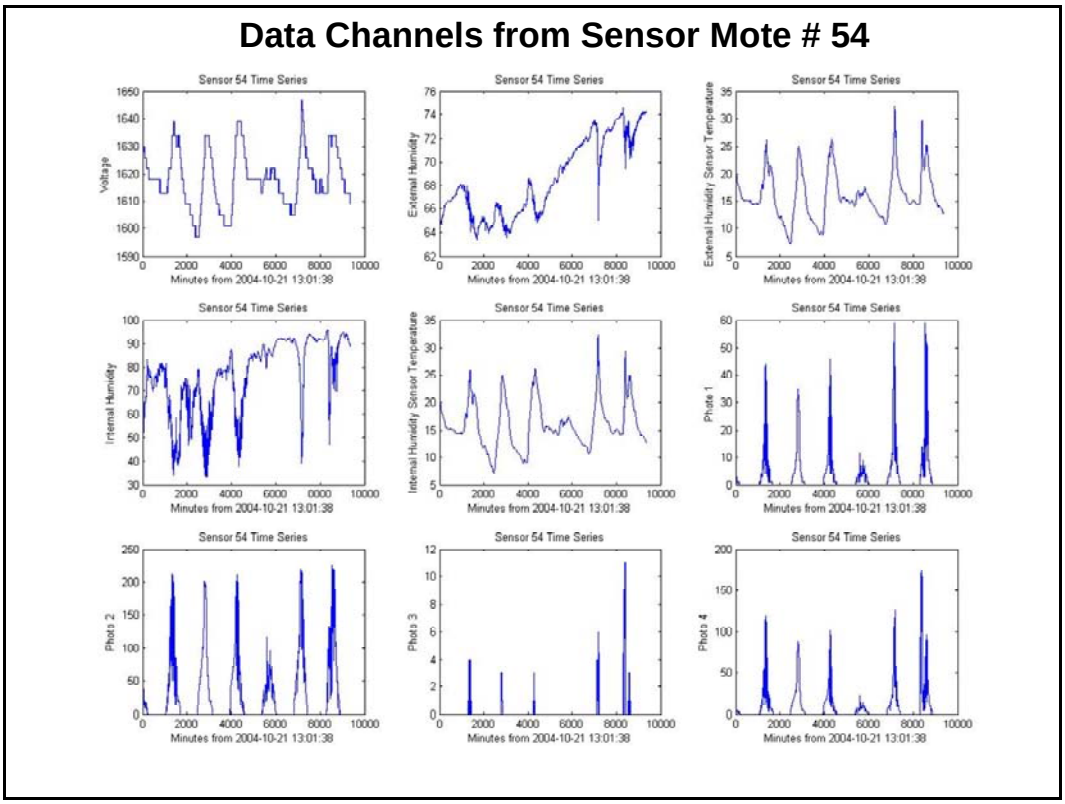

Figure 8-23 Data from Mote # 54 for the period October 21-27, 2004.

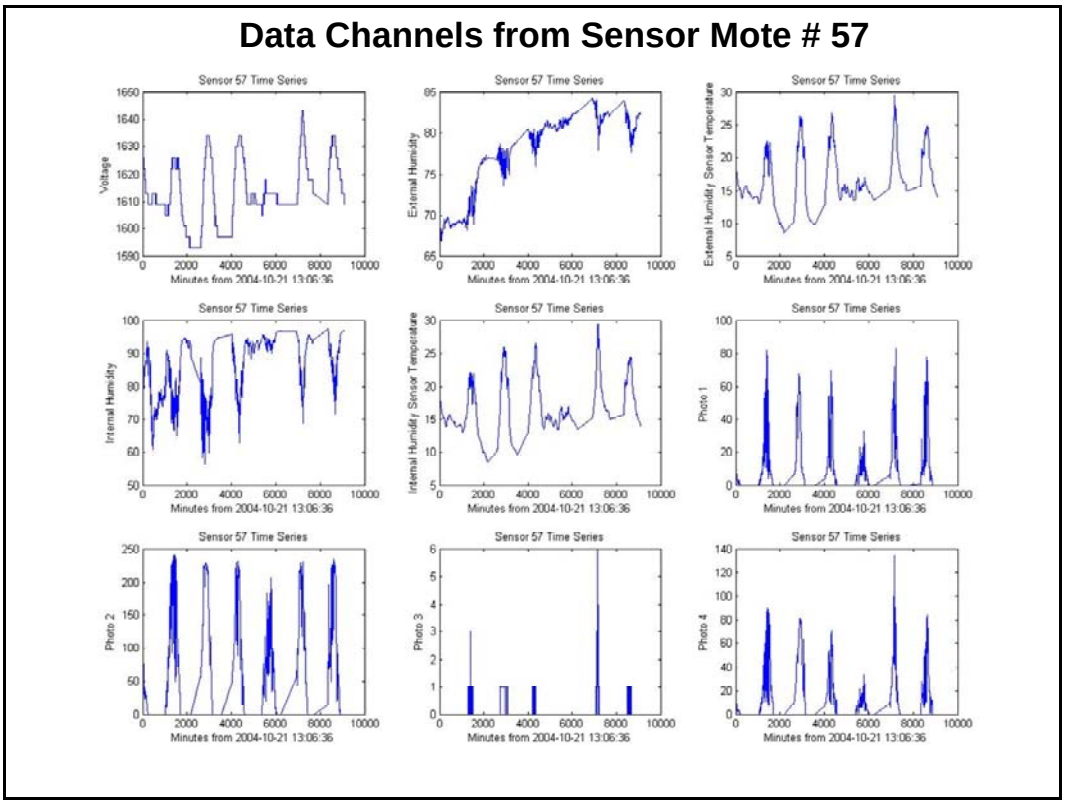

Figure 8-24 Data from Mote # 57 for the period October 21-27, 2004.

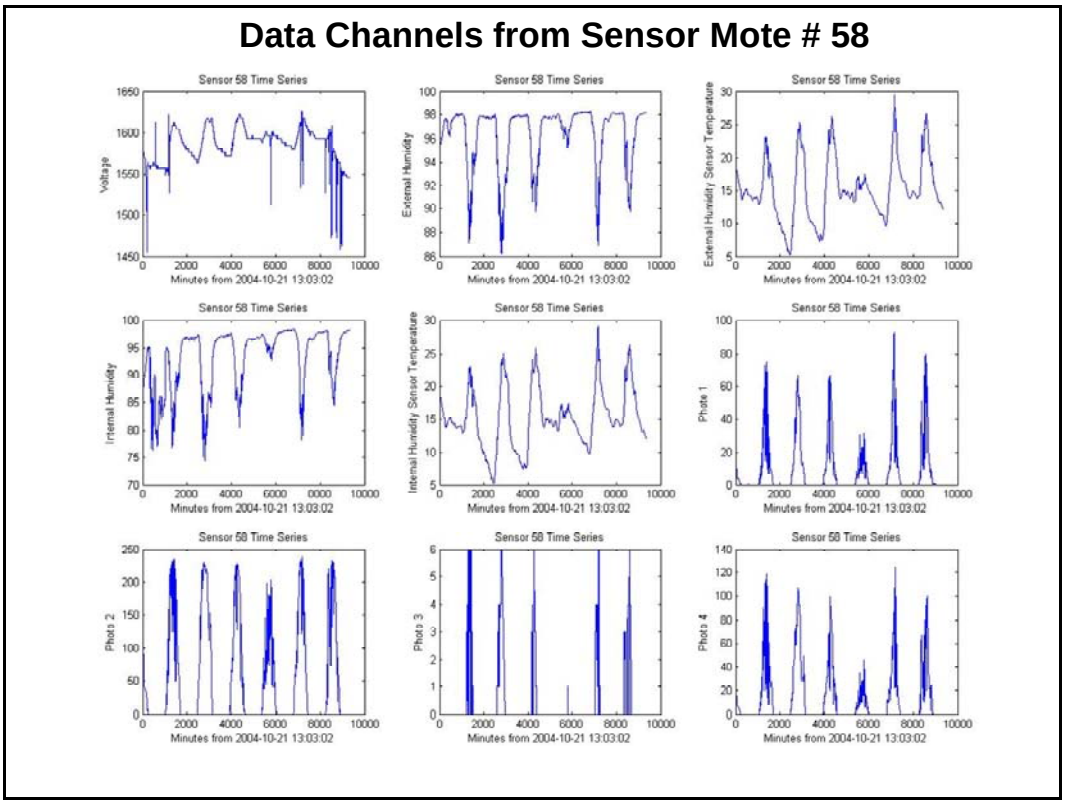

Figure 8-25 Data from Mote # 58 for the period October 21-27, 2004.

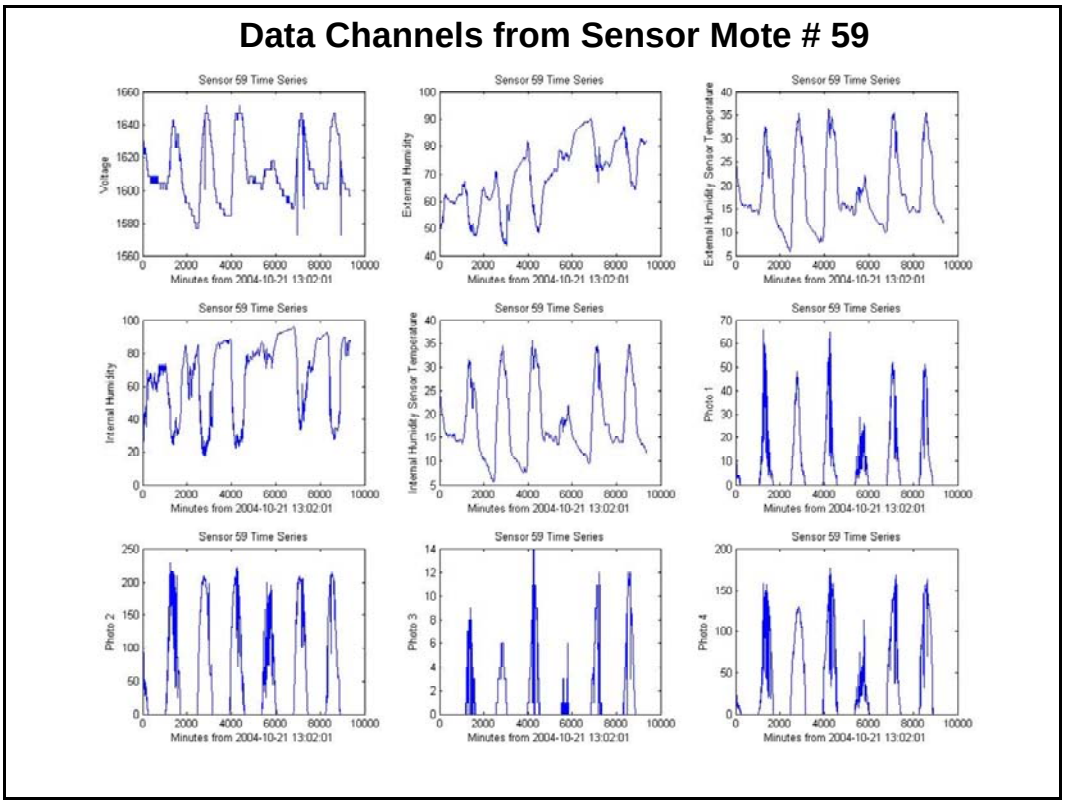

Figure 8-26 Data from Mote # 59 for the period October 21-27, 2004.

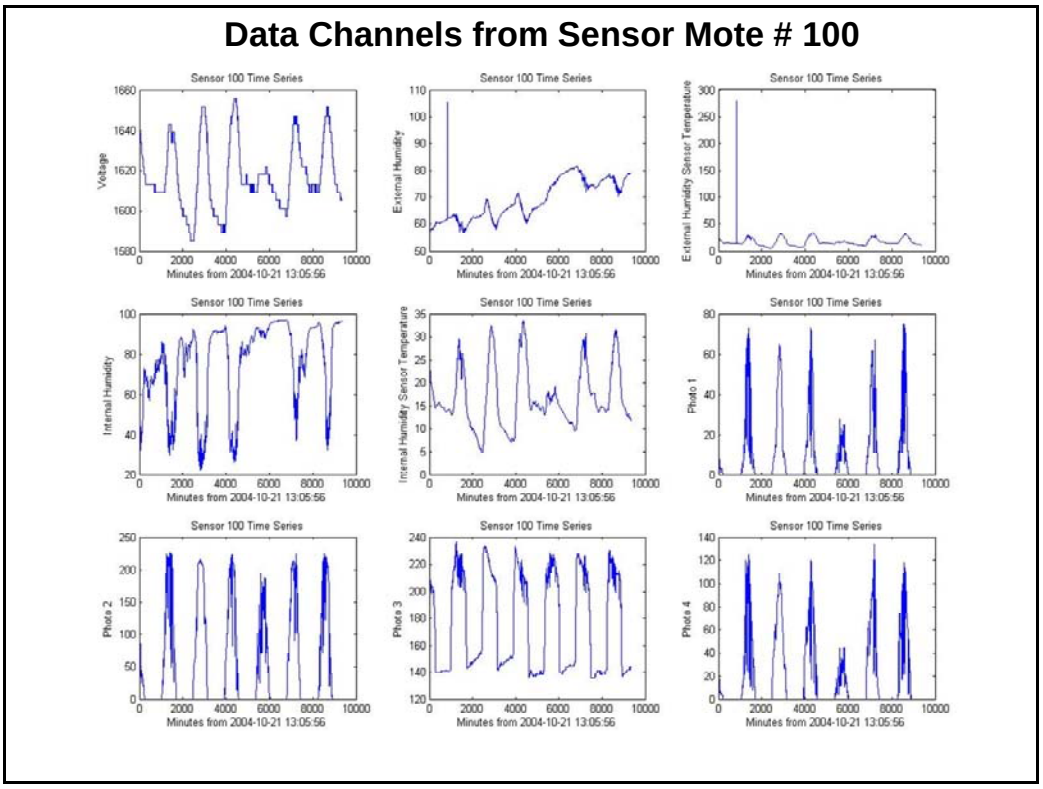

Figure 8-27 Data from Mote # 100 for the period October 21-27, 2004.

8.4 Appendix D: Correlation of Wireless Sensor & Min/Max Sensor Data

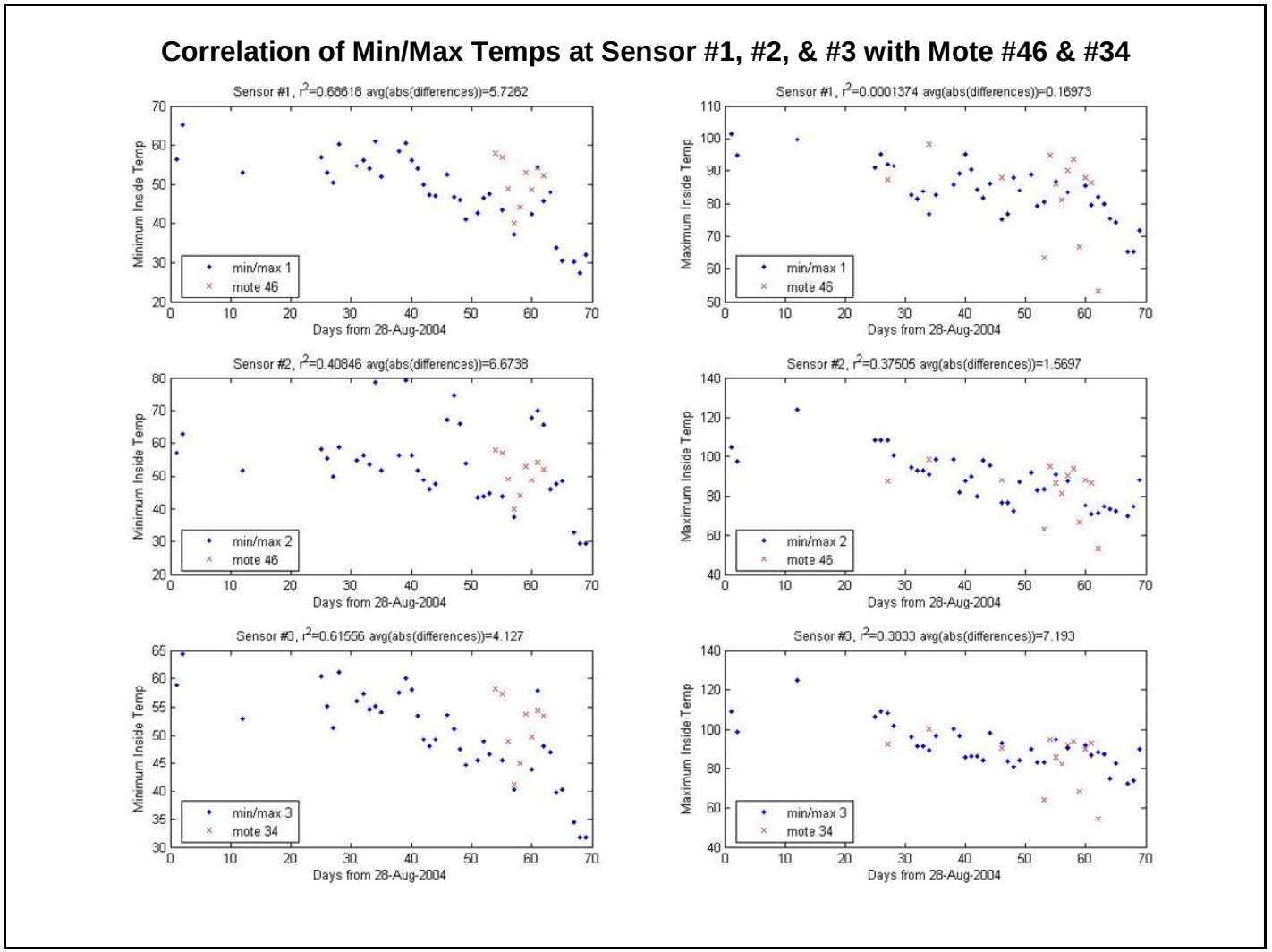

Figure 8-28 Min/max temperature data correlation between min/max sensor #1, #2, & #3 and time series sensor mote #46 & #34.

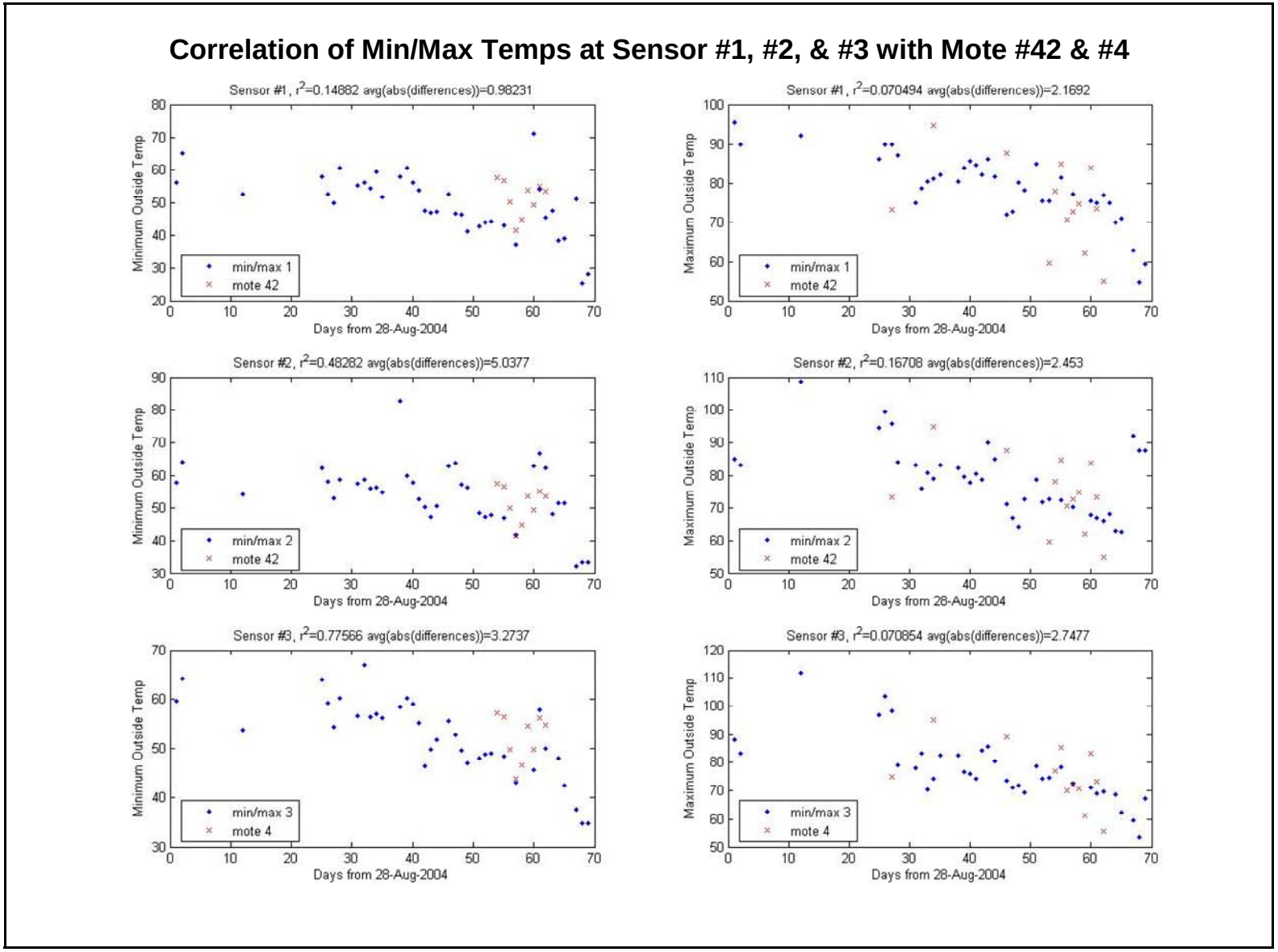

Figure 8-29 Min/max temperature data correlation between min/max sensor #1, #2, & #3 and time series sensor mote #42 & #4.

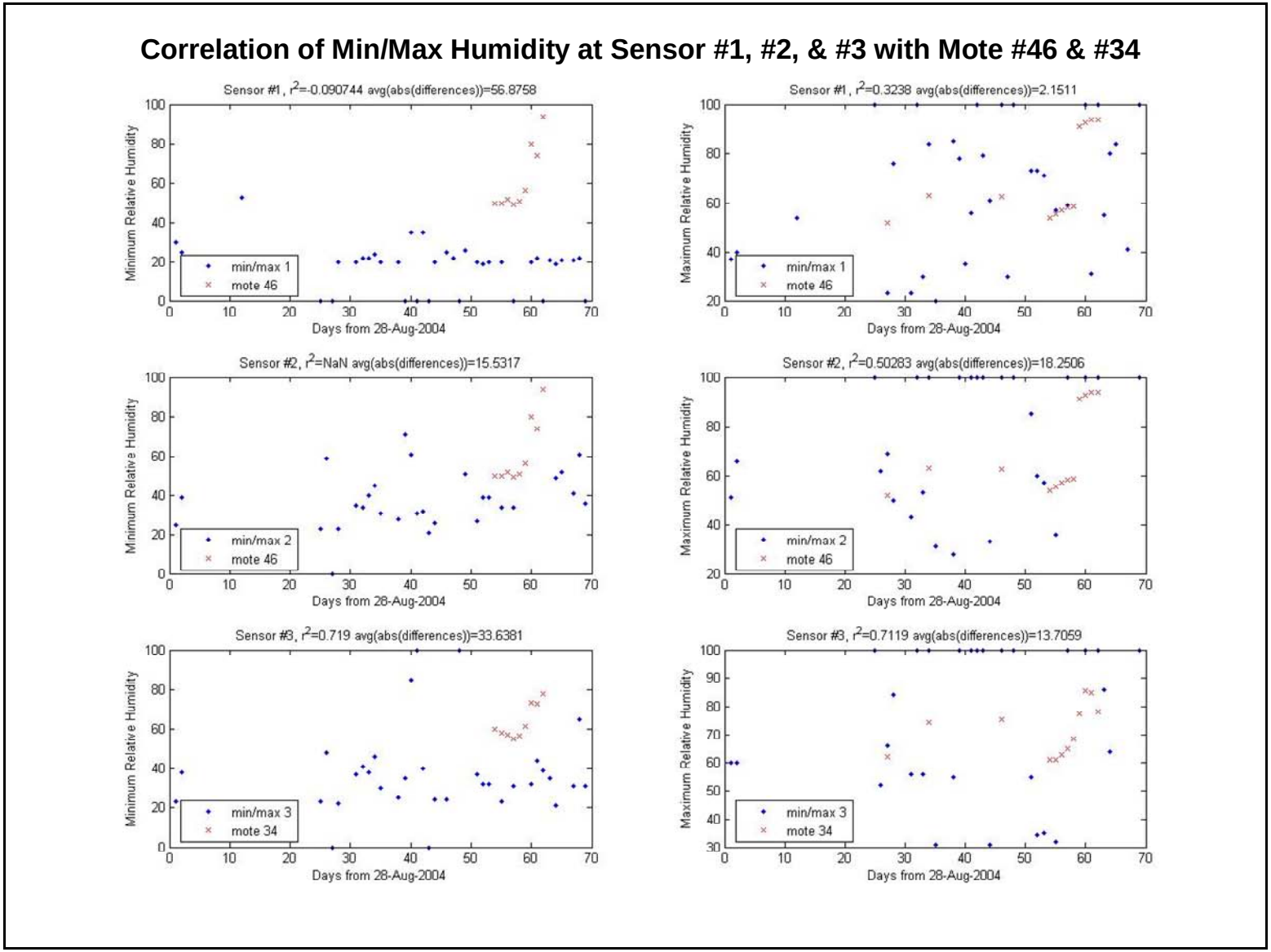

Figure 8-30 Min/max humidity data correlation between min/max sensor #1, #2, & #3 and time series sensor mote #46 & #34.

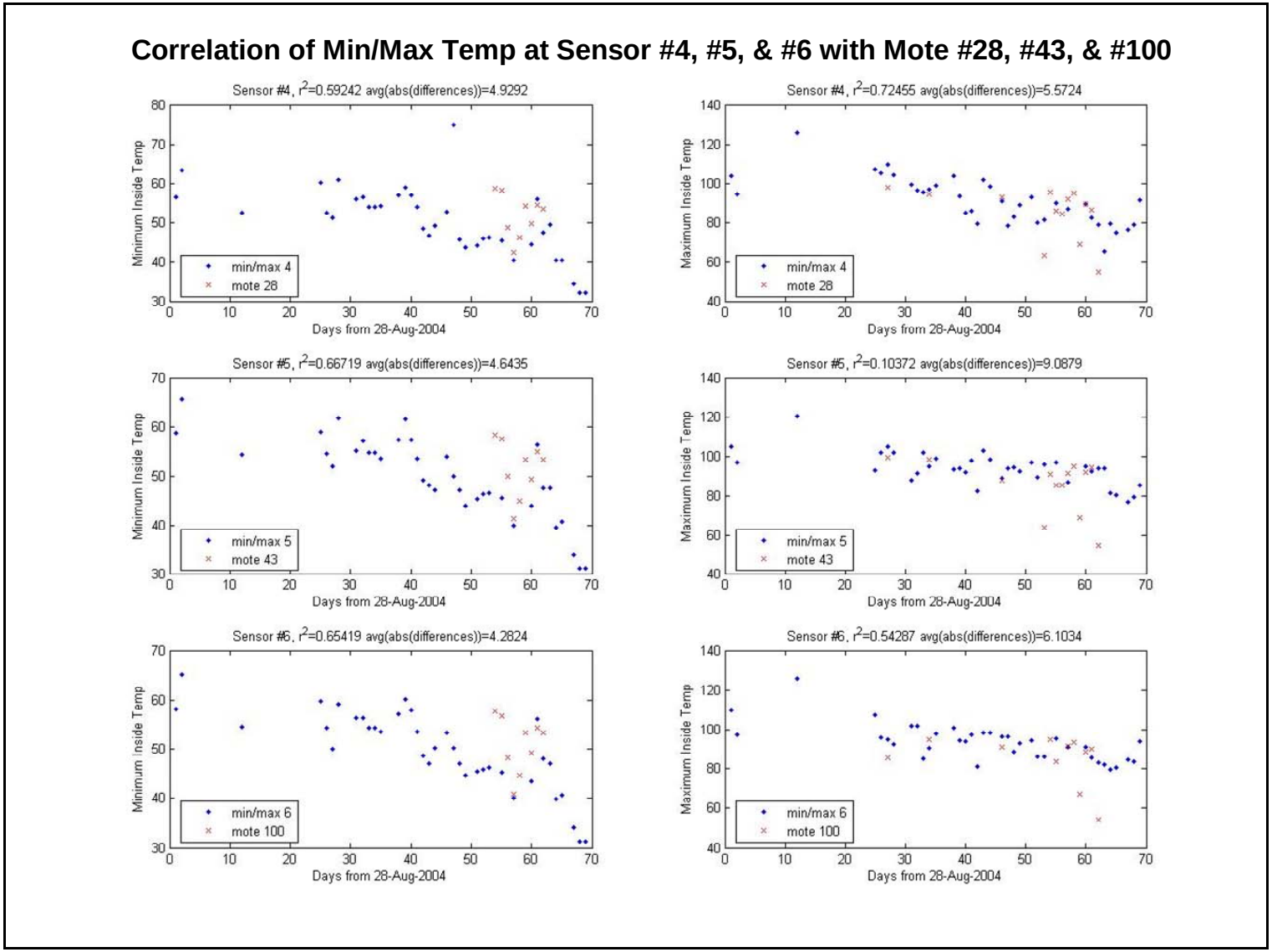

Figure 8-31 Min/max temperature data correlation between min/max sensor #4, #5, & #6 and time series sensor mote #28, #43, & #100.

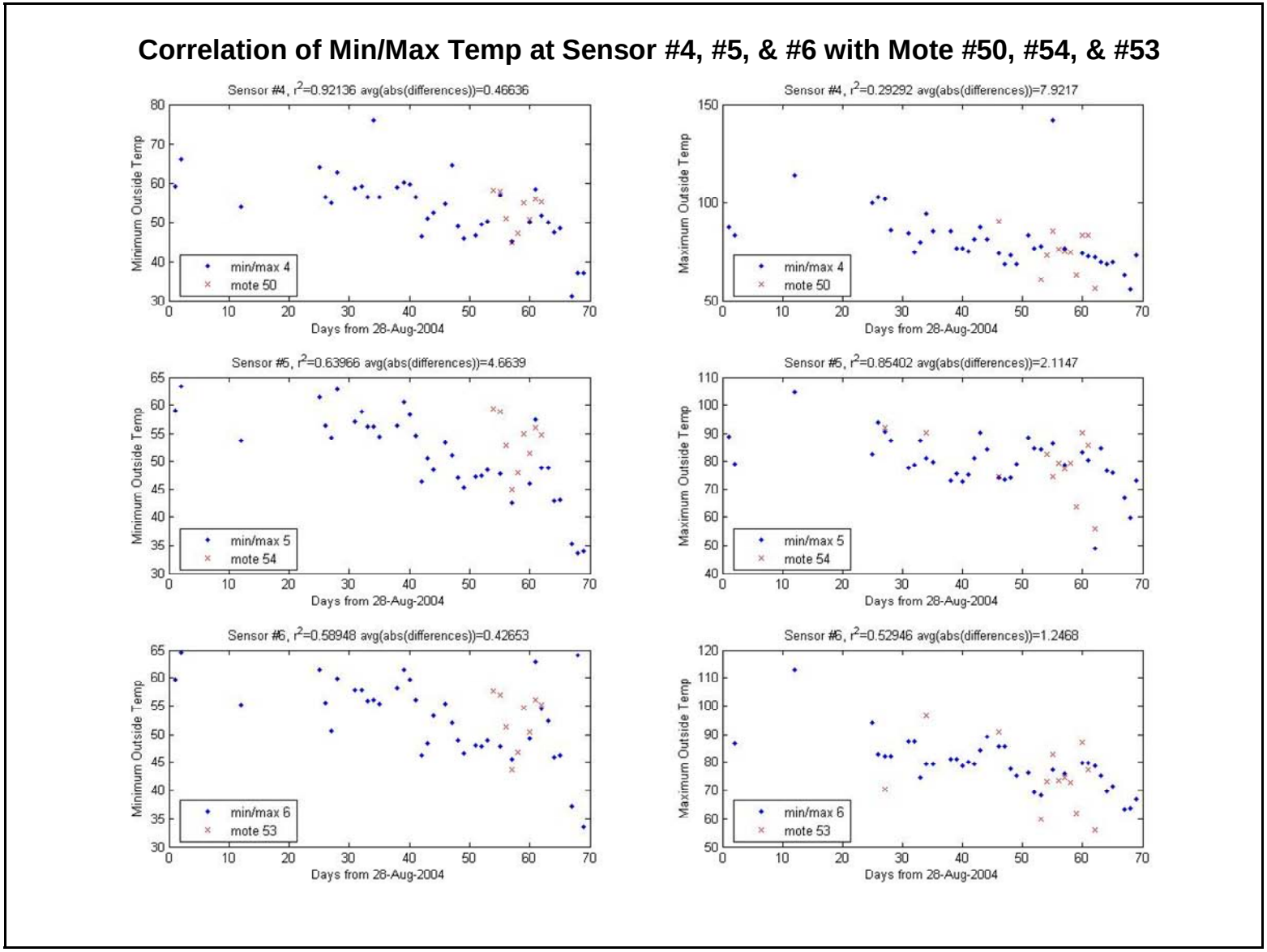

Figure 8-32 Min/max temperature data correlation between min/max sensor #4, #5, & #6 and time series sensor mote #50, #54, & #53.

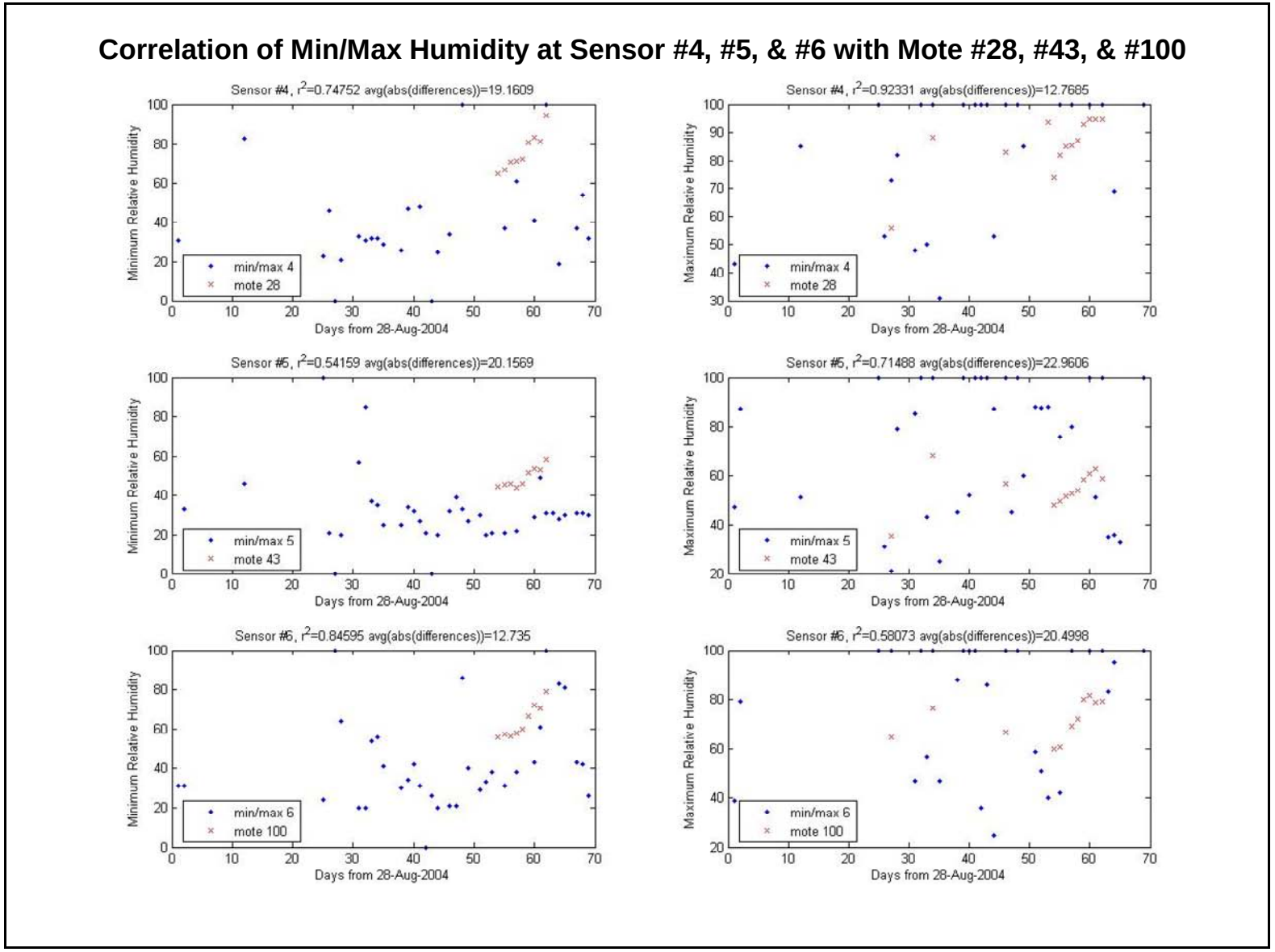

Figure 8-33 Min/max humidity data correlation between min/max sensor #4, #5, & #6 and time series sensor mote #28, #43, & #100.

8.5 Appendix E: Primary Visualization Matlab Scripts

8.5.1 Script for reading in data files

```
function file_data = read_ag_csv_file(file)

[year,month,day,hour,min,sec,nodeid,parent,epoch,voltage,ext_hum,ext_hum_temp,int_hum,int_hum_temp,photo1,photo2,p
hoto3,photo4,press_temp,pressure] = textread(file,'%d-%d-%d %d:%d:%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f');
file_data = [year month day hour min sec nodeid parent epoch voltage ext_hum ext_hum_temp int_hum int_hum_temp
photo1 photo2 photo3 photo4 press_temp pressure];
```

8.5.2 Script for cleaning data, interpolating, and saving in a Matlab standard form

```
clear

x_step = .125; % .125
y_step = .35; % .35
z_step = .075; % .075
t_step = 20; % 20

while (1)
   file = input('Enter the name of the first file the data you wish to analyze came from: ','s');
   fid = fopen(file);
   if (fid == -1)
      fprintf('Invalid File Name\n\n');
      continue;
   else
      fclose(fid);
      break;
   end
end

[smin,smax,gmin,gmax,greenhouse,sensors] = get_geometry('greenhouse_geometry.jzd','sensor_geometry.jzd');
data = read_ag_csv_file(file);
smin_t = 0;
n = size(data,1);
smax_t = (datenum(data(n,1),data(n,2),data(n,3),data(n,4),data(n,5),data(n,6))-
datenum(data(1,1),data(1,2),data(1,3),data(1,4),data(1,5),data(1,6)))*24*60*60;

x = smin(1):x_step:smax(1);
y = smin(2):y_step:smax(2);
z = smin(3):z_step:smax(3);
t = smin_t:t_step:smax_t;

fprintf('Points in x: %d\n',length(x));
fprintf('Points in y: %d\n',length(y));
fprintf('Points in z: %d\n',length(z));
fprintf('Points in t: %d\n\n',length(t));


[yi,xi,zi,ti] = ndgrid(y,x,z,t);
save yi.mat yi;
save xi.mat xi;
save zi.mat zi;
save ti.mat ti;

fprintf('Done reading in data and setting up axes\n');
fprintf('Total number of data points will be %d\n',length(t)*length(x)*length(y)*length(z));

for sensor_index = 10:1:20
```

```
tic
fprintf('Starting to process sensor # %d: %s\n',sensor_index,datestr(clock));

clear('xyzt_d_fix','v_d_fix','v4d_fix','v');

[xyzt_d,v_d,exit_flag] = parse_ag_data(data,sensors,sensor_index);
fprintf('Done parsing: %s\n',datestr(clock));

index = 1;
for i = 1:length(v_d)
   if ((v_d(i) ~= 0)&(~isnan(v_d(i))))
      v_d_fix(index) = v_d(i);
      xyzt_d_fix(index,:) = xyzt_d(i,:);
      index = index + 1;
   end
end
v_d_fix = v_d_fix';
fprintf('Done removing zeros and NaNs in data: %s\n',datestr(clock));

%bins = 193;
%du = 2;
%while (1)
%    [n,centers] = hist(xyzt_d_fix(:,4),bins);
%    if (min(n) <= 0)
%       bins = bins - 1;
%       if (du == 0)
%          break;
%       else
%          du = 1; % down
%       end
%    else
%       if (du == 1)
%          break;
%       else
%          bins = bins + 1;
%          du = 0; % up
%       end
%    end
%end
%fprintf('Done finding bins. # bins = %d: %s\n',bins,datestr(clock));

%bin_width = (max(xyzt_d_fix(:,4))-min(xyzt_d_fix(:,4)))/(bins + 1);

bin_width = 15;
edges = min(xyzt_d_fix(:,4)):bin_width:max(xyzt_d_fix(:,4));
edges(1) = -Inf;
edges(length(edges)) = Inf;
[n,bin] = histc(xyzt_d_fix(:,4),edges);
xyzt_d_fix(:,4) = (bin - 1)*bin_width + min(xyzt_d_fix(:,4)) + bin_width/2;
fprintf('Done "histogramming" the time, width = %f: %s\n',bin_width,datestr(clock));

xu = unique(xyzt_d_fix(:,1));
yu = unique(xyzt_d_fix(:,2));
zu = unique(xyzt_d_fix(:,3));
tu = unique(xyzt_d_fix(:,4));

[yg,xg,zg,tg] = ndgrid(yu,xu,zu,tu);

for i = 1:size(v_d_fix,1)
          v4d_fix(get_index(xyzt_d_fix(i,2),yu),get_index(xyzt_d_fix(i,1),xu),get_index(xyzt_d_fix(i,3),zu),get_index(xyzt_d_fi
x(i,4),tu)) = v_d_fix(i);
end
fprintf('Done creating 4D parameter array: %s\n',datestr(clock));

v = interpn(yg,xg,zg,tg,v4d_fix,yi,xi,zi,ti);
fprintf('Done interpolating: %s\n',datestr(clock));
```

```
    switch sensor_index
        case 10 % voltage
            save voltage_histt.mat v;
        case 11 % ext_hum
            save ext_hum_histt.mat v;
        case 12 % ext_hum_temp
            save ext_hum_temp_histt.mat v;
        case 13 % int_hum
            save int_hum_histt.mat v;
        case 14 % int_hum_temp
            save int_hum_temp_histt.mat v;
        case 15 % photo1
            save photo1_histt.mat v;
        case 16 % photo2
            save photo2_histt.mat v;
        case 17 % photo3
            save photo3_histt.mat v;
        case 18 % photo4
            save photo4_histt.mat v;
        case 19 % press_temp
            save press_temp_histt.mat v;
        case 20 % pressure
            save pressure_histt.mat v;
    end

    fprintf('Finished processing sensor # %d: %s\n\n',sensor_index,datestr(clock));
    toc

end
```

8.5.3 Script for post-processing and visualizing data:

```
while (1)
    fprintf('1: Voltage\n');
    fprintf('2: External Humidity\n');
    fprintf('3: External Humidity Sensor Temperature\n');
    fprintf('4: Internal Humidity\n');
    fprintf('5: Internal Humidity Sensor Temperature\n');
    fprintf('6: Light Level 1\n');
    fprintf('7: Light Level 2\n');
    fprintf('8: Light Level 3\n');
    fprintf('9: Light Level 4\n');
    fprintf('10: Pressure Sensor Temperature\n');
    fprintf('11: Pressure\n\n');

    sensor_index = input('What data would you like to visualize? ');

    if (sum(sensor_index ~= [1 2 3 4 5 6 7 8 9 10 11]) ~= 10)
        fprintf('Invalid Entry\n\n');
        continue;
    else
        break;
    end
end

while (1)
    file = input('Enter the name of the file you wish to analyze: ','s');
    fid = fopen(file);
    if (fid == -1)
        fprintf('Invalid File Name\n\n');
        continue;
    else
        fclose(fid);
        break;
```

```
   end
end

switch sensor_index
   case 1 % voltage
      load voltage_histt.mat;
   case 2 % ext_hum
      load ext_hum_histt.mat;
   case 3 % ext_hum_temp
      load ext_hum_temp_histt.mat;
   case 4 % int_hum
      load int_hum_histt.mat;
   case 5 % int_hum_temp
      load int_hum_temp_histt.mat;
   case 6 % photo1
      load photo1_histt.mat;
   case 7 % photo2
      load photo2_histt.mat;
   case 8 % photo3
      load photo3_histt.mat;
   case 9 % photo4
      load photo4_histt.mat;
   case 10 % press_temp
      load press_temp_histt.mat;
   case 11 % pressure
      load pressure_histt.mat;
end

load yi.mat;
load xi.mat;
load zi.mat;
load ti.mat;

 [smin,smax,gmin,gmax,greenhouse,sensors] = get_geometry('greenhouse_geometry.jzd','sensor_geometry.jzd');
data = read_ag_csv_file(file);

xpts = xi(1,:,1,1);
ypts = yi(:,1,1,1);
zpts = zi(1,1,:,1);
tpts = ti(1,1,1,:);

xsize = length(xpts);
ysize = length(ypts);
zsize = length(zpts);
tsize = length(tpts);

beginning = datenum(data(1,1),data(1,2),data(1,3),data(1,4),data(1,5),data(1,6));

v_reshaped = sort(reshape(v,1,prod(size(v))));

for i = 1:length(v_reshaped)
   if ((v_reshaped(i) ~= 0)&(~isnan(v_reshaped(i))))
      min_val = v_reshaped(i);
   end
end
max_val = max(v_reshaped);

% histogram of data
hist(v_reshaped,50);
title('Histogram of parameter value');
xlabel('Parameter Value');
ylabel('Frequency');

% make isosurface movie at certain value

fprintf('Enter multiple values as a vector, e.g. "[1.2 3 .05]"\n');
```

```
fprintf('Max value: %f, min value: %f\n',max_val,min_val);
val = input('What value would you like to plot an isosurface movie for? ');
for i = 1:length(val)
   if (val(i) > max_val)
      val(i) = max_val;
   end
   if (val(i) < min_val)
      val(i) = min_val;
   end
end

avi_file_name = input('What do you want to call the isosurface movie file? ','s');

avi_movie = avifile(avi_file_name,'FPS',5);
figure;
h = plot_geometry(smin,smax,gmin,gmax,greenhouse,sensors,0);
for i = 1:size(v,4)
   clf(h);
   figure(h);
   plot_geometry(smin,smax,gmin,gmax,greenhouse,sensors,0);
   for j = 1:length(val)
      isosurface(xpts,ypts,zpts,v(:,:,:,i),val(j));
   end
   alpha(.5);
   caxis([min_val max_val]);
   title(datestr(tpts(i)/24/60/60 + beginning,0));
   xlabel('X Position');
   ylabel('Y Position');
   zlabel('Z Position');
   put_text(min(smin(1),gmin(1)),max(smax(2),gmax(2)),(max(smax(3),gmax(3))+1),sensor_index,' Isosurface');
   colorbar;
   grid on;

   frame = getframe(gcf);
   avi_movie = addframe(avi_movie,frame);
   %pause(.1);
end
avi_movie = close(avi_movie);

% do a time/space slice for surf
% this particular one slices along an xy plane and does a movie

fprintf('Enter multiple values as a vector, e.g. "[1.2 3 .05]"\n');
fprintf('Max height: %f, min height: %f\n',zpts(zsize),zpts(1));
z_val = input('What height, z, would you like to plot a value profile movie for? ');
z_index = ones(1,length(z_val));
for i = 1: length(z_val)
   if (z_val(i) > zpts(zsize))
      z_val(i) = zpts(zsize);
   end
   if (z_val(i) < zpts(1))
      z_val(i) = zpts(1);
   end
   min_dif = Inf;
   for j = 1:(zsize-1)
      if (abs(z_val(i)-zpts(j)) < min_dif)
         z_index(i) = j;
         min_dif = abs(z_val(i)-zpts(j));
      end
   end
   if (min_dif ~= 0)
      fprintf('Closest match to z=%f in interpolated data is z=%f\n',z_val(i),zpts(z_index(i)));
   end
end

avi_file_name = input('What do you want to call the filled contour movie file? ','s');
```

```
avi_movie = avifile(avi_file_name,'FPS',5);
figure;
h = plot_geometry(smin,smax,gmin,gmax,greenhouse,sensors,0);
for i = 1:size(v,4)
   clf(h);
   figure(h);
   plot_geometry(smin,smax,gmin,gmax,greenhouse,sensors,0);
   hold on;
   for j = 1:length(z_val)
      contourf_ag(xpts,ypts,v(:,:,z_index(j),i),z_val(j));
   end
   caxis([min_val max_val]);
   colorbar;
   title(datestr(tpts(i)/24/60/60 + beginning,0));
   xlabel('X Position');
   ylabel('Y Position');
   zlabel('Z Position');
   put_text(min(smin(1),gmin(1)),max(smax(2),gmax(2)),(max(smax(3),gmax(3))+1),sensor_index,' Filled Contour');
   grid on;

   frame = getframe(gcf);
   avi_movie = addframe(avi_movie,frame);
   %pause(.1);
end
avi_movie = close(avi_movie);

avi_file_name = input('What do you want to call the surface movie file? ','s');

avi_movie = avifile(avi_file_name,'FPS',5);
h = figure;
for i = 1:size(v,4)
   clf(h);
   figure(h);
   for j = 1:length(z_val)
      surfc(xpts,ypts,v(:,:,z_index(j),i));
      hold on;
      text(avg(xpts),avg(ypts),avg(avg(v(:,:,z_index(j),i))),strcat('z = ',num2str(z_val(j))));
   end
   shading interp;
   alpha(.5);
   axis([xpts(1) xpts(xsize) ypts(1) ypts(ysize) min_val max_val]);
   caxis([min_val max_val]);
   title(datestr(tpts(i)/24/60/60 + beginning,0));
   xlabel('X Position');
   ylabel('Y Position');
   zlabel('Parameter Value');
   grid on;
   put_text(xpts(1),ypts(ysize),max_val+(max_val-min_val)/4,sensor_index,' Surface');
   colorbar;

   frame = getframe(gcf);
   avi_movie = addframe(avi_movie,frame);
   %pause(.1);
end
avi_movie = close(avi_movie);

% do a time space slice for contourf and save it as a movie

fprintf ('\n1: Yes, 0: No\n');
while (1)
   xslice_y_n = input('Do you want to slice along the x axis? ');
   if (sum(xslice_y_n ~= [0 1]) ~= 1)
      fprintf('Invalid Entry\n\n');
      fprintf ('\n1: Yes, 0: No\n');
      continue;
```

```
    else
        break;
    end
end
fprintf ('\n1: Yes, 0: No\n');
while (1)
    yslice_y_n = input('Do you want to slice along the y axis? ');
    if (sum(yslice_y_n ~= [0 1]) ~= 1)
        fprintf('Invalid Entry\n\n');
        fprintf ('\n1: Yes, 0: No\n');
        continue;
    else
        break;
    end
end
fprintf ('\n1: Yes, 0: No\n');
while (1)
    zslice_y_n = input('Do you want to slice along the z axis? ');
    if (sum(zslice_y_n ~= [0 1]) ~= 1)
        fprintf('Invalid Entry\n\n');
        fprintf ('\n1: Yes, 0: No\n');
        continue;
    else
        break;
    end
end

if (xslice_y_n == 1)
    fprintf('\n');
    fprintf('Enter multiple values as a vector, e.g. "[1.2 3 .05]"\n');
    fprintf('Max x: %f, min x: %f\n',xpts(xsize),xpts(1));
    xslices = input('What x (or x"s) would you like to plot a value profile movie for? ');
    for i = 1:length(xslices)
        if (xslices(i) > xpts(xsize))
            xslcies(i) = xpts(xsize);
        end
        if (xslices(i) < xpts(1))
            xslices(i) = xpts(1);
        end
    end
else
    xslices = [];
end

if (yslice_y_n == 1)
    fprintf('\n');
    fprintf('Enter multiple values as a vector, e.g. "[1.2 3 .05]"\n');
    fprintf('Max y: %f, min y: %f\n',ypts(ysize),ypts(1));
    yslices = input('What y (or y"s) would you like to plot a value profile movie for? ');
    for i = 1:length(yslices)
        if (yslices(i) > ypts(ysize))
            yslcies(i) = ypts(ysize);
        end
        if (yslices(i) < ypts(1))
            yslices(i) = ypts(1);
        end
    end
else
    yslices = [];
end

if (zslice_y_n == 1)
    fprintf('\n');
    fprintf('Enter multiple values as a vector, e.g. "[1.2 3 .05]"\n');
    fprintf('Max z: %f, min z: %f\n',zpts(zsize),zpts(1));
    xslices = input('What z (or z"s) would you like to plot a value profile movie for? ');
```

```
    for i = 1:length(zslices)
        if (zslices(i) > zpts(zsize))
            zslcies(i) = zpts(zsize);
        end
        if (zslices(i) < zpts(1))
            zslices(i) = zpts(1);
        end
    end
else
    zslices = [];
end

avi_file_name = input('What do you want to call the slice movie file? ','s');

avi_movie = avifile(avi_file_name,'FPS',5);
figure;
h = plot_geometry(smin,smax,gmin,gmax,greenhouse,sensors,0);
for i = 1:size(v,4)

    clf(h);
    figure(h);
    plot_geometry(smin,smax,gmin,gmax,greenhouse,sensors,0);
    hold on;
    [meshx, meshy, meshz] = meshgrid(xpts,ypts,zpts);
    slice(meshx, meshy, meshz, v(:,:,:,i),xslices,yslices,zslices);
    caxis([min_val max_val]);
    shading interp;
    colorbar;
    title(datestr(tpts(i)/24/60/60 + beginning,0));
    xlabel('X Position');
    ylabel('Y Position');
    zlabel('Z Position');
    put_text(min(smin(1),gmin(1)),max(smax(2),gmax(2)),(max(smax(3),gmax(3))+1),sensor_index,' Slice');
    grid on;
    alpha(.75)

    frame = getframe(gcf);
    avi_movie = addframe(avi_movie,frame);
    %pause(.1);
end
avi_movie = close(avi_movie);
```

8.6 Appendix F: Secondary Visualization Scripts

8.6.1 Script to read in the geometry of the sensors and the greenhouse:

```
function [smin,smax,gmin,gmax,greenhouse,sensors] = get_geometry(greenhouse_geometry_file,sensor_geometry_file)


[greenhouse] = textread(greenhouse_geometry_file,'','delimiter',',');

max_x = max(greenhouse(:,1));
min_x = min(greenhouse(:,1));
max_y = max(greenhouse(:,2));
min_y = min(greenhouse(:,2));
max_z = max(greenhouse(:,3));
min_z = min(greenhouse(:,3));

gmin = [min_x min_y min_z];
gmax = [max_x max_y max_z];

 [sensors] = textread(sensor_geometry_file,'','delimiter',',');
sensors = sortrows(sensors);

smin_x = Inf;
smin_y = Inf;
smin_z = Inf;
smax_x = -Inf;
smax_y = -Inf;
smax_z = -Inf;
for i = 1:size(sensors,1)
   smin_x = min(smin_x,sensors(i,2));
   smax_x = max(smax_x,sensors(i,2));
   smin_y = min(smin_y,sensors(i,3));
   smax_y = max(smax_y,sensors(i,3));
   smin_z = min(smin_z,sensors(i,4));
   smax_z = max(smax_z,sensors(i,4));
end

smin = [smin_x smin_y smin_z];
smax = [smax_x smax_y smax_z];
```

8.6.2 Script to visualize the sensors and greenhouse:

```
function h = plot_geometry(smin,smax,gmin,gmax,greenhouse,sensors,plot_y_n)

% do mesh plot of greenhouse walls and plot of sensor locations with
% their ID's attached to them with the text(x,y,z,num2str(nodeid)) command

h = gcf;
axis([min(smin(1),gmin(1)) max(smax(1),gmax(1)) min(smin(2),gmin(2)) max(smax(2),gmax(2)) min(smin(3),gmin(3))
max(smax(3),gmax(3))]);

draw_rect3(greenhouse(1,:),greenhouse(2,:));
hold on;
draw_rect3(greenhouse(1,:),greenhouse(3,:));
draw_rect3(greenhouse(2,:),greenhouse(4,:));
draw_rect3(greenhouse(3,:),greenhouse(5,:));
draw_rect3(greenhouse(4,:),greenhouse(6,:));
draw_rect3(greenhouse(5,:),greenhouse(6,:));

if (plot_y_n ~= 0)
   for i = 1:size(sensors,1)
```

```
      text(sensors(i,2),sensors(i,3),sensors(i,4),num2str(sensors(i,1)));
   end
end

grid on;
```

8.6.3 Greenhouse geometry file (x,y,z coordinates in units of meters):

```
0,0,0
8.2,18,0
1.7,18,2.45
6.5,0,2.45
4.1,0,3.8
4.1,18,3.4
```

8.6.4 Sensor Geometry File (sensor ID# & x,y,z coordinates in units of meters):

```
38,2.3,3.05,.25
1,2.3,3.05,1.15
27,2.3,3.05,2.1
54,2.3,9.05,.25
25,2.3,9.05,1.15
43,2.3,9.05,2.1
7,2.3,15,.25
20,2.3,15,1.15
59,2.3,15,2.1
42,4,3.05,.25
32,4,3.05,1.15
46,4,3.05,2.1
4,4,9.05,.25
56,4,9.05,1.15
34,4,9.05,2.1
52,4,15,.25
29,4,15,1.15
28,4,15,2.1
51,5.7,3.05,.25
13,5.7,3.05,1.15
39,5.7,3.05,2.1
53,5.7,9.05,.25
58,5.7,9.05,1.15
100,5.7,9.05,2.1
3,5.7,15,.25
10,5.7,15,1.15
26,5.7,15,2.1
```

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