TENSIOMETER CONTROLLED AUTOMATED IRRIGATION SYSTEM FOR CHRISTMAS TREE PRODUCTION

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Abstract.

Irrigation of short rotation trees such as *Abies fraseri* for Christmas tree production is gaining importance in the upper Midwest due to the intensive planting of this species out of its natural range. However, current irrigation scheduling practices rely on empirical observations with very limited automation used. The paper discusses the design, setup, and maintenance of a tensiometer based automated system for *Abies fraseri* trees in a Christmas tree production system. Soil tensiometers equipped with 4-20mA transducers were installed in various plots on drip irrigated *A. fraseri* Christmas tree farms. The transducers were wired to a CR1000 datalogger through an AM16/32 Multiplexer. Water on-demand was controlled by soil moisture tension levels that triggered the stimulation of a CD16AC unit wired to solenoids delivering irrigation water to the various treatments. The datalogger was connected to a remote computer with a static IP address through a raven modem using a wireless cellphone connection. The system functioned according to the design as expected. However, several issues associated with tensiometers, computer programming, and system wiring created some challenges regarding the reliability and transferability of such system to commercial facilities.

Keywords. *Tensiometers, CR1000 datalogger, automated irrigation, Christmas trees, Soil matric potential*

INTRODUCTION

Christmas trees are short rotation perennial crops grown from seed in a nursery for 2 to 5 years, then moved into a plantation where they are raised for an additional 6 to 9 years until the mature harvestable size of approximately 2.1 m (Nzokou et al., 2007). During the last decade, Fraser fir (*Abies fraseri*) has become the most economically important species grown for Christmas tree purposes (Koelling et al., 1992; Nzokou and Leefers, 2007). The species represents about 40% of the estimated 3.5 million trees sold in Michigan, and is also the main species in most producing states in the Midwest and eastern United States (Nzokou et al., 2007). In the upper Midwest, supplemental water must be applied to meet the physiological needs of this species (Koelling et al., 1992; Nzokou and Leefers, 2007). However, in current production practices, irrigation decisions are based on personal observations or empirical knowledge, with a rule of thumb guideline of 2.5 cm of water applied weekly in the absence of rainfall. This practice lags far behind modern irrigation practices in agriculture that use crop assessment, fixed time allocation, or soil moisture variation for scheduling irrigation.

Plant assessment methods include empirical crop water stress index (CWSI) used on a variety of crops including corn (Irmak et al., 2000; Yazar et al., 1999), sunflower (Erdem et al., 2006), watermelon (Orta et al., 2003), and grass and forage crops (Al-Faraj et al., 2001; Payero et al., 2005). Daily changes in diameter (Fereres and Goldhamer, 2003), and visual indices (Jones, 2004) have also been used.

An alternative to crop assessment is to base irrigation scheduling on changes in soil moisture. Irrigating based on changes in soil moisture conditions is relatively simple and easy to apply in practice (Jones, 2004). Soil based assessments are built on constant monitoring of changes in soil moisture content using the hand feel method (Bolen, 1984; VanderGulik, 1997), or a soil moisture measuring device (tensiometers, TDR). This paper reports on the design, set up, and maintenance of an automated irrigation system based on soil moisture variation monitored with tensiometers.

Tensiometer based systems have been used for high input agriculture, in which fertilizers and pesticides are applied. Oki et al. (1996) found that using an automated irrigation system controlled by three different soil tension thresholds resulted in more efficient water use, reductions in pollution run-off, and increase in growth compared to a manually-controlled system. Munoz-Carpena et al. (2005) found that maintaining soil tension levels of 15 kPa resulted in a 73% reduction in water use and no adverse effect on quality compared to a manually irrigated system. Another report indicated that the total marketable yield decreased linearly from tension levels of 10 kPa to 20 kPa (Smajstrla and Locascio, 1996). These studies indicate potential benefits for tensiometer based automated systems for irrigation scheduling.

Automated systems can potentially decrease the overall cost of operating irrigation systems due to reductions in water use (Clark et al., 2007). An automated water on-demand system would be particularly useful for the production of short rotation intensively managed systems such as Fraser fir Christmas tree production. In Fraser fir Christmas tree production, large acreages are often irrigated, taking several days or more to complete. Reducing the labor required for managing these large scale systems could prove substantial and improve the overall profitability of the operation.

Despite the benefits, tensiometers are also known to be difficult to maintain due to their poor adaptability to dry conditions, vacuum breakage, and variability in measurements (Nzokou et al., 2007). Therefore, challenges associated with the inclusion of these devices into an automated irrigation system need to be identified and addressed.

The goal of this project is to design, construct, and implement a tensiometer based automated irrigation system for Fraser fir Christmas tree plantations that would: 1) use existing technologies, 2) apply water based on changes in soil moisture content, 3) provide operational flexibility, 4) interface with a computer for system changes, data collection, and system modifications. This paper describes the hardware and software components of the system and presents preliminary plant growth data achieved under this automated method.

MATERIAL AND METHODS

Location and Design

The automated irrigation systems were constructed for experimental purposes at two Christmas tree farms in Michigan. The farms are located in Horton, Michigan and Sidney, Michigan. At the Horton farm, the existing drip irrigation system was excavated and modified to divide the field into smaller zones allowing independent control of irrigation for each zone. At the Sidney location, a new drip irrigation system was designed and constructed for the purpose of this study (Figure 1).

There are 5 components to the system: 1) a standard drip irrigation system with a 3.75 cm (1.5 inch) main line and a 2.5 cm (1 inch) sub-main line supplying drip lines with low pressure water flow, 2) solenoid valves controlling the water flow to each irrigation zone, 3) soil moisture tensiometers placed in each irrigation zone, 4) a control system including datalogging equipment and a controller able to activate the solenoids. The system is based on a simple feedback loop with the soil moisture tension (tensiometer reading) used as control parameter, and a water cycle starting when the soil moisture tension reaches a predetermined threshold. At each location, the field was divided into smaller (approximately 0.2 acres) irrigation zones for various irrigation treatments as indicated in figure 1.

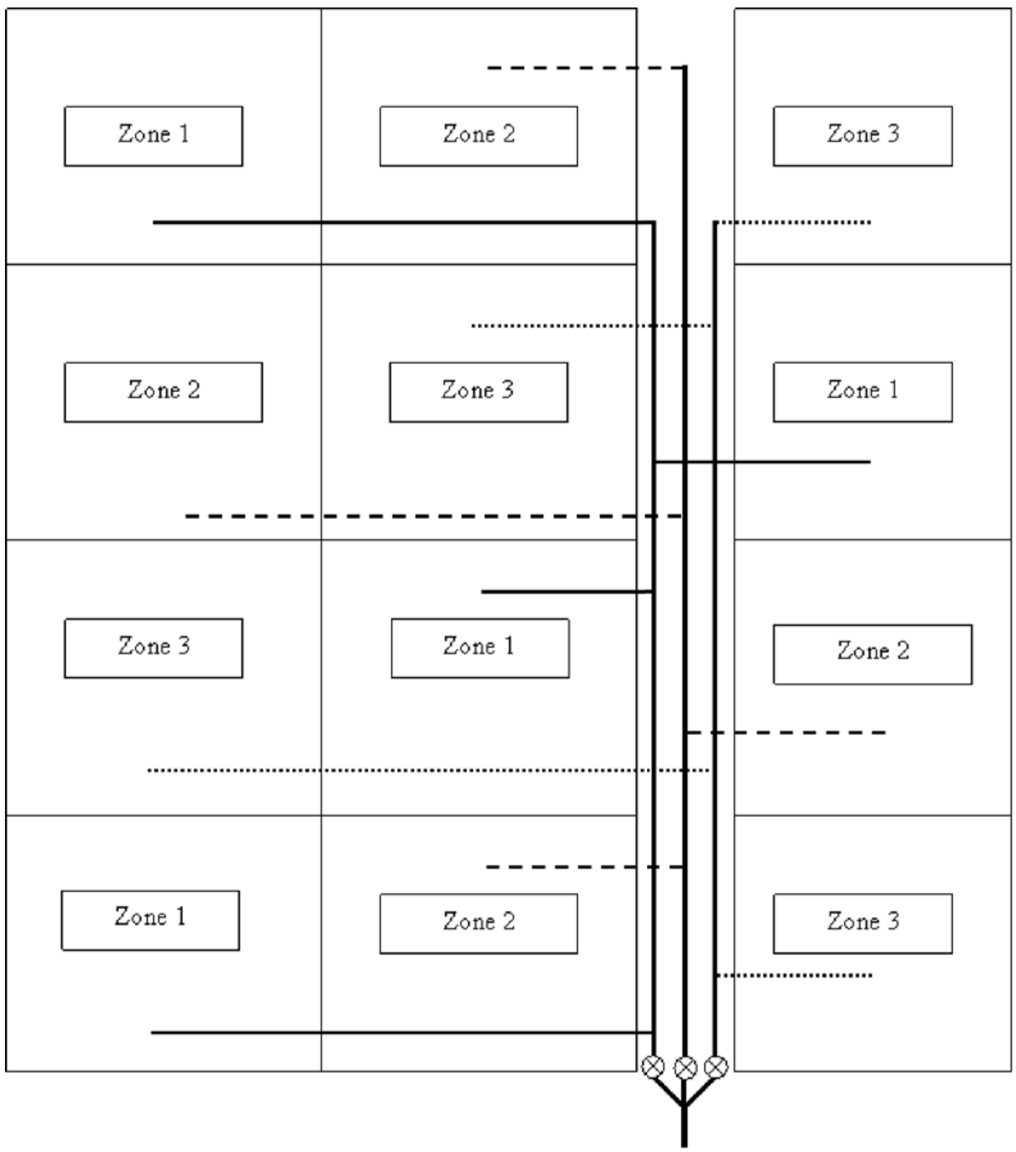

Figure 1: Field divided into irrigation zones controlled by solenoids. Each zone corresponds to an irrigation treatment.

For each system, a CR1000 datalogger was installed in an enclosure on a CM10 tripod (Campbell scientific Co.). Weather sensors including a 03101 R.M Young Sentry anemometer, a TE525 tipping bucket rain gage, a HMP50 temperature and relative humidity probe, and a CS300 pyranometer (Campbell Scientific Co.) were installed on the tripod and wired to the datalogger for continuous measurement (Figure 2).

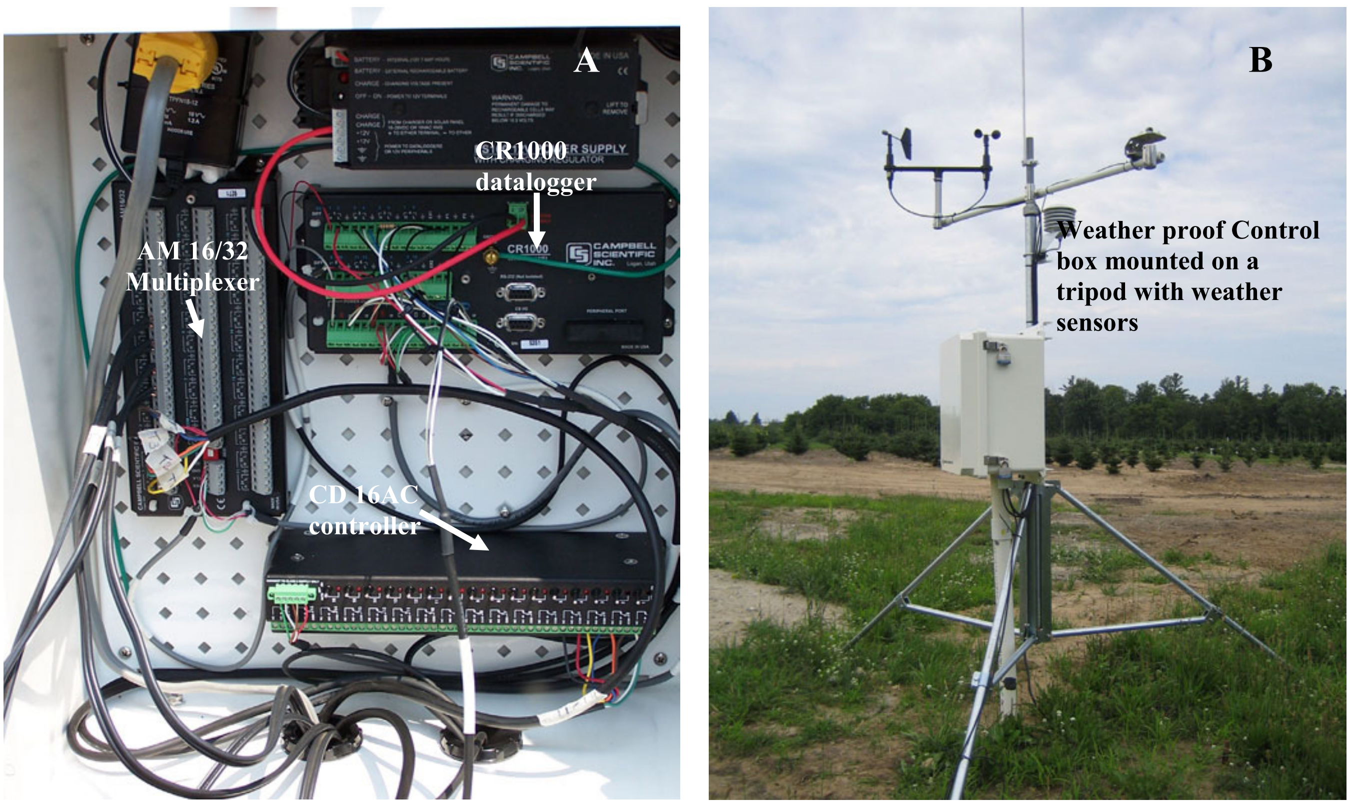

Figure 2. CR1000 datalogger, multiplexer and control in enclosure (A), and overall system mounted on tripod with weather sensors (B).

Tensiometers

A tensiometer is a device made of a sealed plastic (or glass) tube with a porous ceramic tip on one end, a screwable cover and a vacuum gauge on the other end (Figure 2). The vacuum gauge is calibrated in centibars (or cb) and graduated from 0 to 93cb (this can vary with the brand or tensiometer type). Tensiometers are sold as 12” (30 cm), 18” (45 cm), and 24” (60 cm). The tube is air tight and water filled and under vacuum when in operation. When installed in the ground, water moves freely from the ceramic tips into the surrounding soil environment as the ground dries, or from the soil into the tubes as the moisture content into the surrounding soil increases. Tensiometers measure the soil water matric potential, defined by the Soil Science Society of America (Young and Sisson, 2002) as “the amount of work that must be done per specific quantity of pure water from a specified source to a specified destination”. As soil dries with warm weather and no or little rainfall, water is drawn out of the instrument, reducing the water volume in the tube and creating a partial vacuum that is registered on the gauge. Consequently, the drier the soil, the greater the force per unit area holding the remaining water in the soil, and the higher the reading. Conversely, when it rains and soil receives water, the vacuum created inside the tube will suck water back into the tube and lower the gauge reading.

For this project we used 30 and 60 cm tensiometers (Irrometer Company Riverside, CA) placed in each zone. The 30 cm tensiometer was used to make irrigation decisions and the 60 cm tensiometer helped understand the soil moisture gradient from the surface to deeper soil profiles. Tensiometers were placed along the drip line and spaced away from each drip emitter so that the distance from the tree to the emitter was approximately the distance from the tensiometer to the nearest emitter (Hung, 1995).

Each tensiometer was equipped with a 4-20 milliamp (ma) remote sensing units (RSU) for connection to a CR1000 data logger (CR1000 Campbell Scientific Logan, Utah). The RSU units were all calibrated by the Irrometer Company and ready to use when received. Due to the large number of tensiometers connected to the system, an AM16/32 multiplexer was used to increase the number of connection possibilities. The data logger read 12-24 millivolts (mv) when it scanned each terminal. Consequently, it was necessary to add 100 ohm resistors (CURS100) to each terminal to convert the 4-20 ma signal into a voltage signal that the datalogger could recognize during each scan. All tensiometers were hard wired to the datalogger using this approach.

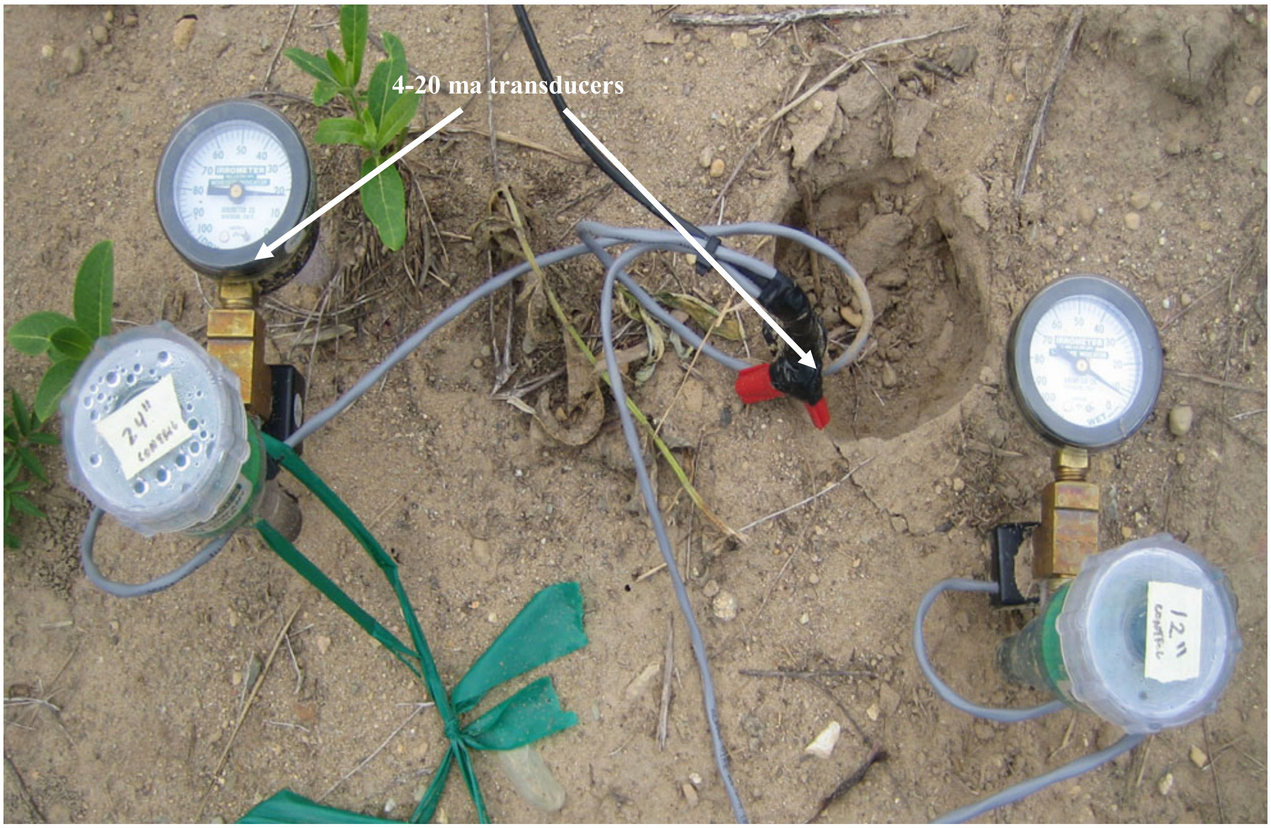

Figure 3: Tensiometers (30 cm and 60 cm) installed in the ground. Each tensiometer had a vacuum gauge and 4-20 ma transducer wired to the multiplexer.

In addition, a SDM-CD16AC AC/DC channel controller (Campbell Scientific Co.) was added in order to automate the system. The channel controller was wired to the datalogger and connected to the solenoids (5V, 24V relays) controlling each irrigation zone or treatment. The overall wiring diagram connecting all the pieces and devices of the system is presented in Appendix 1.

Irrigation decisions

Water application was controlled by soil moisture tension levels specified for each treatment with goal of investigating the effect of low to high soil matric potential (tensiometer readings) on the height and diameter growth of trees at various stages of the rotation.

Table 1: Irrigation thresholds (on/off tolerances) to maintain various tension levels in zones controlled by a tensiometer based automated irrigation system.

Zone	Tensiometer depth	Stop irrigation	Target tension	Start irrigation
1	30 cm		Non-irrigated	
	60 cm			
2	30 cm	≤ 13 kPa	15 kPa	≥ 17 kPa
	60 cm			
3	30 cm	≤ 23 kPa	25 kPa	≥ 27 kPa
	60 cm			
4	30 cm	≤ 33 kPa	35 kPa	≥ 37 kPa
	60 cm			
5	30 cm	≤ 43 kPa	45 kPa	≥ 47 kPa
	60 cm			

The margin was set at ±2 kPa tension range for each of the different zones, with the exception of the non-irrigated zone. If the tension exceeded this range, the system would activate a valve that would initiate an irrigation event in the corresponding zone. Irrigation would stop when the tension reached the low range of the ±2 kPa threshold, based on the target tension. For example, for the 15 kPa irrigation threshold, the system would start if soil moisture tension reached 17 kPa, and would stop as soon as it was below 13 kPa. As indicated, irrigation decisions were based on the reading of the 30 cm tensiometer. Even so, trigger levels could be adjusted to take into account soil physical characteristics, the tree water needs of the tree and its growth stage. The computer program for the specific instruction described above will be as follows:

Monitoring and wireless communication

The CR1000 data logger offers different options for collecting data. Using either PC400 or LoggerNet data logger support software (Campbell Scientific), direct connection is possible using the RS-232 port, linking a portable computer and the datalogger with a serial cable. However, a direct cable connection requires a computer and an operator at the location of the data logger for data download (Cheek and Wilkes, 1994; Shukla et al., 2006). Therefore, the option of using wireless communication was very attractive for constant remote monitoring of the data logger and the overall functioning of the system. For this purpose, a Raven100 CDMA Airlink Cellular Modem (Campbell Scientific Inc.) was purchased and wired to the RS-232 port on the datalogger. The Raven100 CDMA modem has a PN 18285 1dBd Owni Directional antenna mounted on the system tripod. A data account using a dedicated IP address for each system was setup with Alltel for remote connection to each station from our office.

This setup allows greater flexibility with regular monitoring of the system, and data collection. In addition, customization of the software and data collection allowed for incorporation of charts and graphs for a visual representation of data and alarm notifications in the event of a malfunction.

The system was operated by a computer program created using "shortcut" in the PC400 software (Campbell Scientific). The program developed using visual basic coding language, defines units, and provides specific instructions with all coefficients and transformations necessary to collect data that are directly usable. Furthermore, several table definitions summarizing data based on a predefined schedule were created and inserted into the program. The first page example of the program is presented in Appendix 1.

Budgeting and cost considerations

Compared to a manually controlled irrigation system, an automated system is more expensive initially due to purchasing the equipment. However, these costs averaged over the life of the irrigation system are likely to be considerably cheaper than the manually controlled alternative. Table 3 shows a summary of costs of the various components and labor required to implement a system of this nature. Based on our experience, the cost for building an automated irrigation system on 1 ha is $7,692. The cost of a drip irrigation system, exclusive of automation, can range from $1,500 to $3,500/ha with maintenance costs ranging from $50 to $200/ha/yr (Ayars et al., 2007). The $2,500 irrigation system cost is based on the assumption that 80% of the cost is for drip tube, 15% for main and sub-mainlines, and 5% for connections and valves. Depending on the quantity, quality, and complexity of the desired components, costs could vary greatly. The cost for adding the automation as part of the irrigation system ($4,942) is based on the assumption that one 30 cm and 60 cm tensiometer represent a single zone; therefore, increasing the number of zones will add to costs. Labor associated with the automated system ($1000) relates to the time required to setup and properly implement the system in situ. Due to the complexity of connecting and programming an automated irrigation system, there may be the possibility of a lengthy learning curve or need for technical assistance, which could increase costs. Since the tensiometers require connection to the data logger and peripherals, increasing the tensiometers beyond the means of the data logger might require the purchase of additional peripherals, further increasing costs. The wireless service necessary to access, modify, and view the workings of the irrigation system is based on a standard limited access data account and can vary among wireless carriers and usage. The cost summary listed in Table 2 is presented as a starting point to the investment required in building an automated system.

Table 2: Total costs for components and materials associated with building an automated irrigation data based on actual expenses with a local irrigation supplier.

	Automation / Measuring System		Irrigation System	
Item	**Description**	**Costs ($)**	**Description**	**Costs ($)**
Components	CR1000 Data logger	1,350	Trickle tube[2]	2000
	SDM-CD16AC Controller	695	Pipes: main, sub-main[2]	375
	AM16/32 Multiplexer	560	Connections / valves[2]	125
	Tensiometer (30 cm)	165		
	Tensiometer (61 cm)	185		
	CURS100 Resistor	52		
	Wireless Modem	340		
	LoggerNet Software	545		
	Wireless service[1]	50	Installation	100
Labor	Set up	1,000	Maintenance[3]	150
Subtotals		**4,942**		**2,750**
Total cost				**7,692**

[1]cost/mo [2]cost/ha [3]cost/yr

DATA EXAMPLE

Tensiometer readings

A summary example of tensiometer readings for the 15 KPa and 25 KPa treatments from July 8, 2006 (Day of the year 189) and October 25, 2006 (Day of the year 275) is presented in Figure 4). During the period from DOY 189 to DOY 230, there was no rainfall in the area. The figure indicates that readings for both tensiometers increased as the site conditions become drier, until the water cycle started at day 202 for the 15 KPa. The 25 KPa tensiometer continued to rise until day 210, dropping following a watering event that started once the reading for reached 27 KPa (irrigation threshold for the 25 KPa tensiometer). Similar cycles were repeated between day 223 and day 230. Following these two irrigation cycles, soil moisture remained below irrigation thresholds for both tensiometers until the end of the measurement period on October 25.

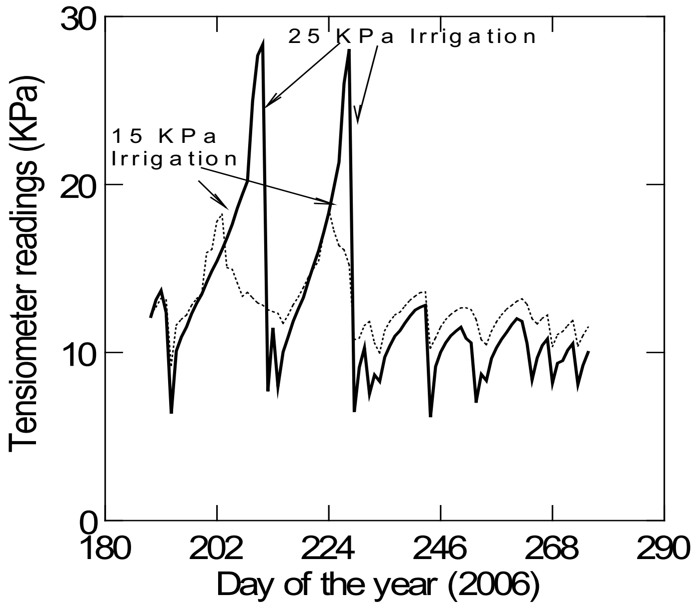

Figure 4. Tensiometers (15 KPa and 25 KPa) readings for the period between July 8 and October 25, 2006. Readings above the threshold for each level was followed by a quick drop caused by an irrigation event.

Influence of irrigation treatment on growth

The effect of the various irrigation treatments on growth response is summarized in Figure 5. The height growth for each tree measured was normalized by dividing by initial growth to account for size differences in trees before treatments were applied. The overall trend of the data shows a positive response to irrigation treatments for trees in smaller height classes (0.6m< to 1.2-1.5m) in 2006 (Fig. 5-A) and 2007 (Fig. 5-B). The relative growth of trees receiving irrigation at the 15 and 25 KPa thresholds was significantly higher ($P<0.05$) than non-irrigated trees for height classes 0.6 m and below (2006 and 2007) and 0.6-0.9m (2006). Growth response was generally positive for medium size trees (0.9-1.5m) for both years, but results were more variable and not always statistically significant. Height growth of tall trees (1.5m and above) did not respond to irrigation.

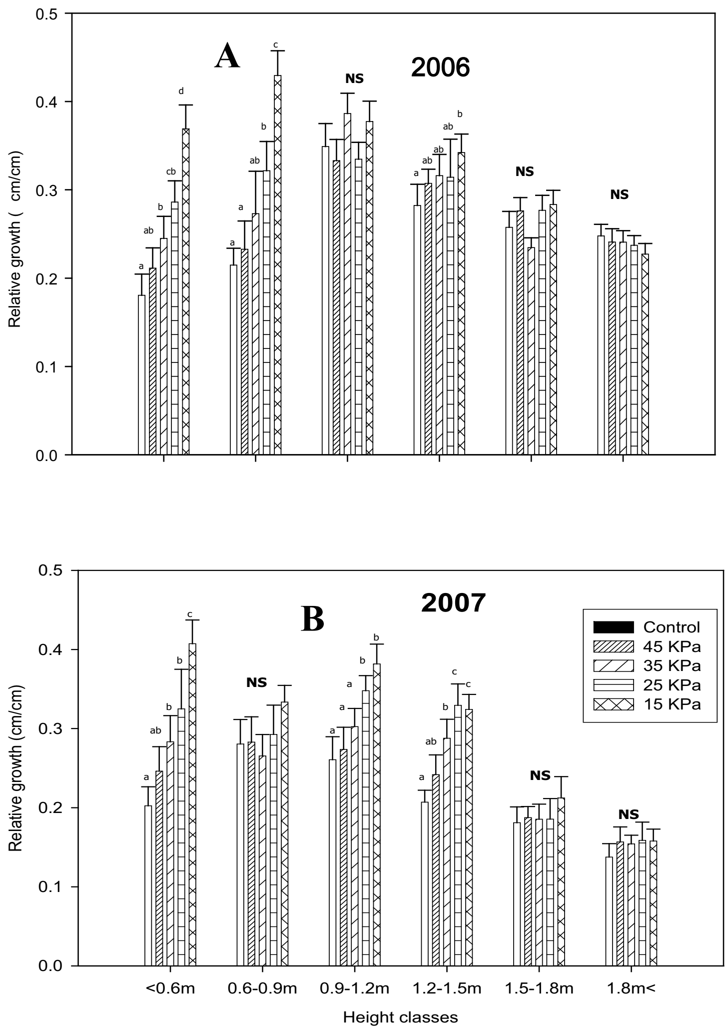

Figure 5: Mean relative height growth (cm/cm) by height classes in 2006 (A) and 2007 (B) in Horton. Similar letters indicate no significance between treatments means ($P < 0.05$)

Problems and considerations

Although an automated irrigation system should be much less problematic than a manually controlled system, there are still a few areas of concern that should be considered. Tensiometers need to be installed and removed at the beginning and end of each growing season if freezing winter temperatures are expected. We observed a tendency for the tensiometers to have a break in vacuum and no communication between the ceramic tip and the vacuum gauge. This was commonly due to dry conditions requiring a refill of the tensiometer. Sometimes, the break in vacuum was caused by leaks in connection requiring the adjustment or replacement of the 'O' ring sealing the connection between the ceramic tip and the tensiometer tube. Furthermore, poor contact between the ceramic tip and the soil also led to erroneous readings, and it was necessary to change locations and reinstall the tensiometer.

Tensiometers also have a tendency to fail in very dry soils. If an irrigation plan calls for excessive drying between irrigation events, other soil moisture measurement instruments such as TDR should be considered. Also, soil tension reported is only true for the location the tensiometer is present, emphasizing the importance of instrument placement. Tensiometer placement relative to emitters should be similar in relation to emitter spacing for the trees. Aside from tensiometer functionality, care should be taken in securing exposed wire connections. The data logger and controllers experienced few problems in both of our research locations. Periodically, the data collected produced errors, but few data points were missing or erroneous. This was more likely to occur when the frequency of data collection was increased. Using wireless data acquisition, connecting quickly and maintaining a long connection was often problematic, due to intermittent cellular coverage in the area where the data logger and modem were placed. For this reason, it is advisable to check which wireless carriers offer the strongest coverage in the area to be irrigated.

CONCLUSION

An automated irrigation system providing water on-demand was designed and constructed at two Christmas tree farms in Michigan. Elements of the system included datalogging equipment, an irrigation controller, and a set of tensiometers used as trigger for the irrigation of the various zones. The system generally functioned properly with irrigation events starting immediately as soon as the soil water tension reached the pre-determined threshold for each irrigation zone. Growth data collected indicated that low soil matric potential setup (values of 15KPa and 25 KPa) significantly improved height and basal area growth of *Abies fraseri* trees of less than 1.2 m in height. Results were more variable for trees of 1.2 m in height or higher, indicating their greater ability to withstand droughty conditions probably due to their more extensive and far reaching root system. However, there were several challenges associated with the extensive wiring required to setup such a system, proper design of computer programs needed to operate all sensors and controllers used for the system, as well as maintenance of tensiometers for accurate reading of soil moisture tension. Experiences from this project indicate that it will be challenging to implement such a system in large scale commercial operations without the active support of qualified irrigation technicians.

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Appendix 1: Wiring diagram for CR1000, AM16/32 and Tensiometers

WIRING FROM CR1000 TO AM16/32	
CR1000	**AM16/32**
RES	C4
CLK	C5
GND	GND
12V	12V
COM ODD H	3H
COM ODD L	3L
COM EVEN H	EX2
COM EVEN L	SE 7

AM16/32 TO CURS100 WIRING (AM16/32 BANKS 1 – 10)	
AM16/32	**CURS100**
ODD H	H
ODD L	L
GROUND	GROUND
EVEN H	NOT USED
EVEN L	NOT USED

CURS100 TO TENSIOMETER WIRING	
CURS100	**TENSIOMETER**
H	SIGNAL RETURN
L (JUMPER WIRE TO G)	N/A
G (JUMPER WIRE TO L)	N/A
12VDC SIDE OF TENSIOMETER TO 12VDC SUPPLY	

Appendix 1: First page example of computer program used

```
'CR1000
SequentialMode

'Declare Variables and Units
Dim LCount_11
Public Batt_Volt
Public SlrkW
Public SlrMJ
Public WS_mph
Public WindDir
Public AirTF
Public RH
Public Rain_in
Public Irr_cBars(11)
Public CD16Source(16) As Boolean

Units Batt_Volt=Volts
Units SlrkW=kW/m²
Units SlrMJ=MJ/m²
Units WS_mph=miles/hour
Units WindDir=Degrees
Units AirTF=Deg F
Units RH=%
Units Rain_in=inch
Units Irr_cBars=cBars

'Weather data
DataTable(syd_30mn,True,-1)
  DataInterval(0,30,Min,10)
  Average(1,SlrkW,FP2,False)
  WindVector (1,WS_mph,WindDir,FP2,False,0,0,0)
  FieldNames("WS_mph_S_WVT,WindDir_D1_WVT,WindDir_SD1_WVT")
  Average(1,AirTF,FP2,False)
  Sample(1,RH,FP2)
  Totalize(1,Rain_in,FP2,False)
EndTable

DataTable(syd_60mn,True,-1)
  DataInterval(0,60,Min,10)
  Totalize(1,SlrMJ,IEEE4,False)
  WindVector (1,WS_mph,WindDir,FP2,False,0,0,0)
  FieldNames("WS_mph_S_WVT,WindDir_D1_WVT,WindDir_SD1_WVT")
  Maximum(1,AirTF,FP2,False,True)
  Average(1,AirTF,FP2,False)
  Sample(1,RH,FP2)
  Minimum(1,AirTF,FP2,False,True)
  Totalize(1,Rain_in,FP2,False)
  Minimum(1,Batt_Volt,FP2,False,False)
EndTable
```