Understanding the Public Benefits of Sensor Networks

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Introduction

In this module, we will look at the potential impacts of wireless sensor networks on public infrastructure. Private benefits focus on on-farm savings that can be achieved with sensor networks, while public benefits focus on impacts beyond the farm. Growers are likely to adopt sensor networks because of their private benefits, but the same mechanisms that increase profitability (reduced water and nutrient use) also have significant public benefits as well. This module will estimate some of those public benefits.

Brief historical perspective

In the 1940's through the 1970's, the "green revolution" occurred thanks to the development and worldwide distribution of technologies associated with crops, improved genetic resources, irrigation, and synthetic fertilizers, pesticides, and fungicides. There was also a shift to large-scale agricultural production and improved farm management techniques, that dramatically increased crop yields and world food supplies (Evenson and Golin, 2003; Paarlberg, 2010).

Agricultural outputs increased greatly during the "green revolution".

These shifts, however, perpetuated agricultural practices that use significant amounts of water and energy, and involved applications of fertilizers and chemicals that have significant adverse environmental impacts (Pingali, 2012). While the green revolution increased food production and generated significant positive economic returns to land owners, farmers, and agribusinesses, there was also environmental degradation of soil and waterways, which generated problems that continue to persist today.

Increased agricultural intensity also impacted soil and water through chemical application and water and nutrient runoff.

Making agriculture more sustainable is typically more difficult to implement through best management practices or other means, since this usually involves costs that are not offset by expected increases in revenues (Behe et al., 2012). Recent research involving sensor networks might be an exception to this rule. We have found significant cost savings associated with sensor network adoption under a variety of production conditions. These savings have led to increases in profits, which have led to payback periods of several months to a few years. It is this increase in profitability that suggests that sensor networks will be more widely adopted by growers. As these systems become more widely adopted, the public benefits associated with their use increases.

In this module, we will discuss the public benefits of sensor network adoption, and take a look at some of the potential public benefits of these systems. The numbers that are presented here are based on information that we have gathered as part of this project. We attempted to be realistic in our estimates based on results seen at the grower partners that have been involved in this project. A follow-up study will be necessary to determine the actual public impacts of sensor networks.

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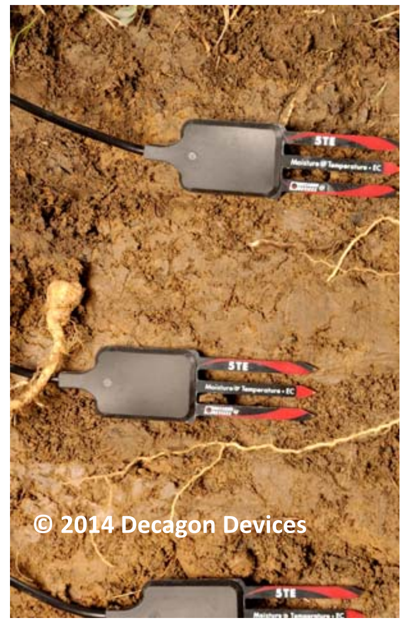
Why are growers likely to adopt WSIN?

There are three main reasons why growers may choose to invest in a sensor network:

1) **Monetary savings** – Sensors have been shown to reduce production time, inputs (water, fertilizer etc.) and labor for irrigation.

2) **Provide information that is not currently available** – sensor information is very accurate, is available in real time using a variety of devices (computer, smartphone, tablets etc.), and the information is provided as a number (for example % volumetric water content) so it is easy to understand. This allows growers to make better decisions.



3) **The use of sensors has environmental benefits** – sensors can reduce environmental impacts through reductions of in the application of water and nutrients, and in the emission of carbon dioxide. These reductions can either be on farm (gas or diesel irrigation pumps, reduced groundwater pumping, etc.), or through reduced outputs from the grid energy (coal, nuclear, etc.).

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Pattern of technology adoption

Technologies typically become more refined over time, as demand increases.

Most new technologies have a long, often winding path from development to widespread adoption. This path is shown in Figure 1 below. Consider the adoption of cell phones, and wireless networks as we discuss this topic. When cell phones were first introduced, even commercially, they had limited uses, and were much less advanced compared with the smart phones of today.

When a technology is first developed or discovered, it has very limited impact in terms of those who use it and in terms of its public or environmental benefits. As the technology is improved, it becomes more useful and accessible, and becomes more widely adopted. Sensor networks have gone through the research and experimentation phases of development, and are currently entering the commercialization phase (see Figure 1 below). The development of sensor networks has reached the point where they are beginning to be adopted by growers. As this technology becomes more widely adopted, public benefits will continue to accrue at an increasing rate. Although it is difficult to predict the total impact of sensor networks, we will present a number of different scenarios, to provide you with an idea of the type of impacts that are possible with the adoption of sensor networks.

As technologies mature, there are many benefits, including adding more features, and addressing problems that have arisen.

There are a number of factors that affect the public benefits that are realized with the adoption of sensor networks, including the speed and extent of adoption, and the effectiveness of the technology. How quickly sensor networks are adopted affects how long it takes for environmental benefits to increase. If we use our cell phone example above, it took less than 20 years for this technology to spread rapidly in the US and around the world.

The cost of a technology, and how the cost relates to the benefits that are seen by growers impacts how fast the use of sensor networks will spread. The more benefits that growers accrue from the system, the more likely they are to see it as beneficial to them. Likewise, as the total number of growers that have adopted sensor networks increases, public benefits will increase as well. The effectiveness of sensor networks (both the system itself and how it is used) will impact pollution reduction. As sensor network technology and our ability to use it improves, environmental benefits will also increase. At the operation level, each grower has to integrate sensor networks into their growing decisions. The more information from sensor networks is applied, the higher the environmental benefits will be at that operation.

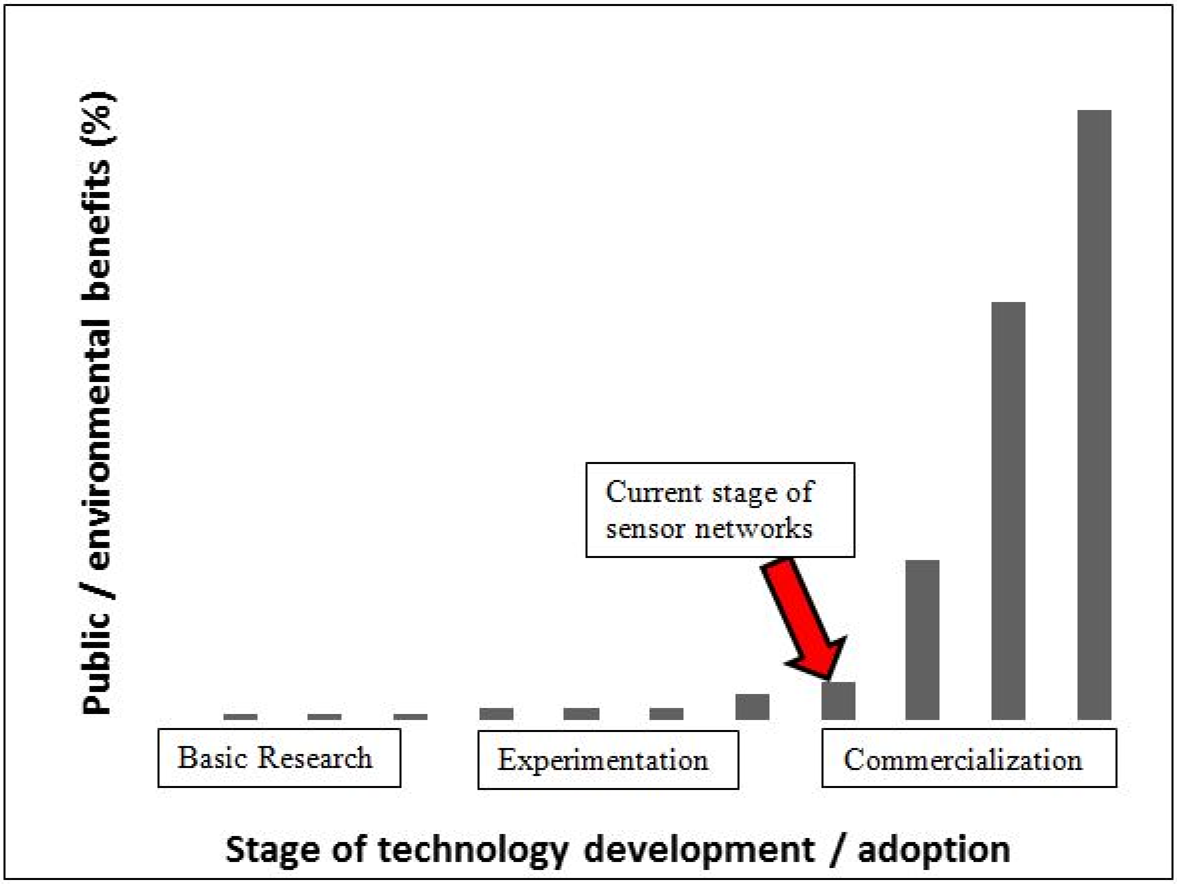

Figure. 1. Theoretical environmental benefits that can be gained from emerging wireless sensor irrigation network technologies (Modified from National Research Council, 1997).

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Impacts of reductions in water usage and CO_2 emissions

Now that we have taken a look at where this technology currently is, let's take a look at some of the possibilities.

As part of this project, we estimated regional water use for greenhouse, container, and field operations using information from the USDA Census of Agriculture Farm and Ranch Irrigation Survey (FRIS) and values from Majsztrik (2011) (for more information, see Majsztrik et al., 2013, which is at the end of this module). We then assumed that average water use would decline by 50% with the adoption of sensor networks. This 50% per operation reduction was combined with adoption rates of 25%, 50%, 75%, and 100% of growers in a region to determine long-term impacts. No attempt was made to estimate the rate or speed of adoption (the slope of the curve in Fig. 1). Other assumptions regarding percent reductions in water use and regional adoption rates were used to test the sensitivity of results. It is possible that water savings from the adoption of WSIN technology by growers who are water-limited, but not land-limited, would result in an increase in acreage of ornamental production rather than water use saving, but for the purposes of this analysis, we assumed that no additional land is used for ornamental production.

Reducing irrigation pumping volumes would also reduce electricity requirements, and greenhouse gas emissions.

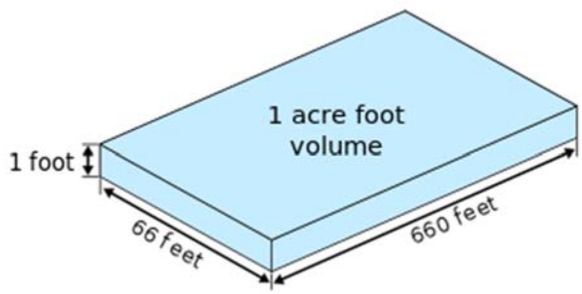
Since sensors networks use less water to grow plants, this should lead to pumps running less often, and therefore fewer emissions, either from diesel pumps or power plants that produce electricity. Using a region-specific mix of energy production (coal, nuclear, diesel, renewables etc.), we estimated reductions in carbon dioxide (CO_2) emissions based on the amount of energy that would be saved by pumping less water.

Regional water volume and the amount of carbon dioxide used to move water were calculated using FRIS data and standard CO_2 calculators. The percent reductions using sensor networks were then applied across the whole region, depending on the percent adoption rate. For example the regional CO_2 totals were multiplied by 0.5 (50% percent reduction in an operation), and then multiplied by 0.25 (for the 25% adoption rate). The details about how these analyses were performed can be found in the full paper (Majsztrik et al., 2013).

Now let's take a look at some of the potential reductions that can be seen at the national scale with sensor network adoption.

Reductions in water use

Table 1 shows the estimated annual reduction in water for greenhouse, container and field production under 2 scenarios, 50% and 100% adoption rates (both assuming a 50% reduction in water volume per operation with the use of sensor networks). At both 50% and 100% adoption, container operations would have the highest reduction at 28,911 and 57,823 million gallons respectively followed closely by field operations at 23,436 and 46,872 million gallons respectively.



An acre foot of water is the amount of water it takes to fill one acre of area, one foot deep with water, or about 325,000 gallons of water.

For perspective, there are about 325,000 gallons per acre foot. The 50% reduction total of 58,790 million gallons of water equals about 181,000 acre feet vs 362,000 acre feet of water for the 100% adoption scenario. The average household uses about 140,000 gallons of water a year, so 181,000 acre feet is enough water for about 420,000 households, or 840,000 households under the 100% scenario.

Summary information is presented here. A list of water reductions by region can be found at the end of this module.

Table 1. Annual potential national reduction in water use (gallons) through the adoption of sensor networks for ornamental production. Water reductions are reported using a 50% and 100% adoption scenario, and assuming a 50% reduction in water use once sensor networks are adopted at an operation.

Region	Operation type	Annual reduction in water use (million gallons)[z]	
		50% adoption	100% adoption
All regions	Greenhouse	6,442.2	12,884.4
	Container	28,911.8	57,823.6
	Field	23,436.5	46,872.9
	Total	**58,790.4**	**117,580.9**
[z]1 gal.= 3.785412 L			

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Reductions in carbon dioxide

Over half of the CO_2 reductions were achieved through container operations 22,552 tons out of 39,939 tons (56%) of CO_2 reduced for the 50% adoption scenario. Field operations accounted for almost 3 times the volume of reduction compared with greenhouse operations. Region specific information can be found at the end of this module. Reductions are based on how much reduced pumping energy would be required to move the smaller amount of water, and factors in the regional mix of fuels (gasoline, diesel, coal etc.) that are used.

Table 2. Annual potential regional reductions in carbon dioxide emissions by using sensor networks. Annual CO_2 reductions are based on a 50% reduction in pumping volumes, at 50% and 100% of ornamental operations.

Region	Operation type	Annual reduction in CO_2 emissions (tons)[z]	
		50% adoption	**100% adoption**
All regions	Greenhouse	4,429	8,859
	Container	22,552	45,104
	Field	12,958	25,914
	Total	39,939	79,879

[z]1 ton = 0.9071847 Mg

Reductions in nitrogen and phosphorus runoff

Since fertilizer and water are typically not a large portion of operating expenses, growers may be over applying these inputs to maximize growth. There is evidence that application rates of nutrients are higher than plant requirements (Majsztrik, 2011). This practice leads to negative environmental consequences as excess fertilizers exit the root zone and enter ground or surface waters causing nutrient pollution in these water bodies. Sensor networks would provide real-time information about soil and substrate fertility levels to help growers make more informed decisions about fertilizer application rates. The potential benefits of sensor networks for fertilizer reductions are highlighted in the next few pages.

In order to estimate nitrogen and phosphorus savings, we constructed two different scenarios for each type of operation. A "conservative scenario" (Table 3) assumed that N and P application rates would be reduced by 25% for greenhouse operations (through reduced water application), with no change in container and field operations. By irrigating more efficiently, runoff rates were assumed to be reduced by 25% for all operation types. The "Optimistic scenario" (Table 4) had larger reductions in application rate for greenhouse and container, with larger reductions in runoff rate for all 3 operation types. Reductions in nutrient runoff rate were not measured as part of this project, and the runoff rates presented here are meant to be illustrative. These scenarios were then used to estimate potential reductions in N and P runoff across the country.

Table 3. Conservative scenario for adjusting nutrient application and runoff rates with the use of wireless sensor irrigation networks (WSIN), compared with current baseline values without WSIN.

	With WSIN	
Operation type	**Application rate**	**Runoff rate**
Greenhouse	25% less than baseline	25% less than baseline
Container	Unchanged from baseline	25% less than baseline
Field	Unchanged from baseline	25% less than baseline

Table 4. Optimistic scenario for adjusting nutrient application and runoff rates with the use of wireless sensor irrigation networks, compared with current baseline values without WSIN.

	With WSIN	
Operation type	**Application rate**	**Runoff rate**
Greenhouse	40% less than baseline	40% less than baseline
Container	25% less than baseline	40% less than baseline
Field	Unchanged from baseline	40% less than baseline

Reductions in nitrogen and phosphorus runoff

Table 5 shows the reductions in N and P runoff under both the conservative and optimistic scenarios by operation type. Container production had the highest estimated reductions ranging from 567,496 pounds to 2,496,981 pounds for N and 337,433 pounds to 1,484,701 pounds for P. To put these numbers in perspective, we can use an application rate of 200 lb/acre for N and 100 lb/acre for P to determine how much land we would "remove" from production using sensor networks. At a rate of 200 lb/acre for N, that would be like removing 2,800 to 12,500 acres of container production. At a rate of 100 lb/acre for P, that would be like removing 3,375 to 14,850 acres of container production. Greenhouse operations had the second highest reductions although the reduction rates were about 5 to 18 times lower than those estimated for containers. Field reductions were the lowest and ranged from almost 7,000 pounds to over 22,000 pounds. Regional breakdowns can be found at the end of this module.

Field operations in the eastern part of the United States typically have vegetated buffers between rows which stabilize the soil and reduce sediment runoff where rainfall is more abundant.

Bare ground production methods are typically used in drier climates to reduce water loss, but they pose a problem with nutrient and sediment runoff during rain events.

Application rates for all values were based on data collected from site visits to operations in Maryland, since no regional information was available. Greenhouse and container production practices are likely similar in terms of application rates of fertilizer across the country. Fertilizer application and runoff in field operations are likely variable from one region to another. For field production, practices in Maryland are likely similar to production practices along the East Coast, where most growers likely use grassed buffers around production areas. This may not be the case in other regions, like the West Coast, where bare ground production is typical. For this reason, P runoff was not estimated, since management practices, which have a large impact on P runoff rates, are varied across the country.

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Table 5. Potential reductions in annual nitrogen (N) and phosphorus (P) runoff in pounds (lb) for ornamental production with adoption of wireless sensor irrigation networks using two different scenarios (conservative and optimistic) with two different adoption rates (50% and 100%). Reductions in nitrogen (N) and phosphorus (P) emissions are based on conservative and optimistic scenarios (Table 3 and 4 respectively). Note: P values are not reported for field operations because reliable data for P runoff could not be obtained outside of Maryland.

		Conservative scenario				**Optimistic scenario**			
		50% adoption		**100% adoption**		**50% adoption**		**100% adoption**	
Region	**Operation type**	**Pounds of N reduced[z]**	**Pounds of P reduced[z]**	**Pounds of N reduced[z]**	**Pounds of P reduced[z]**	**Pounds of N reduced[z]**	**Pounds of P reduced[z]**	**Pounds of N reduced[z]**	**Pounds of P reduced[z]**
All regions	Greenhouse	48,246	63,301	96,492	126,600	70,576	92,087	141,153	184,176
	Container	567,496	337,433	1,134,991	674,865	1,248,492	742,351	2,496,981	1,484,701
	Field	6,896	---	13,794	---	11,034	---	22,070	---
	Total	622,638	400,734	1,245,277	801,465	1,330,102	834,438	2,660,204	1,668,877

[z]1 lb = 0.4535924 Kg

Reductions: Combined

Total reductions (Table 6) are based on 100% adoption in ornamental production, which represents the maximum benefit under these conditions (the complete table can be found at the end of this module). Almost 50% of water and $C0_2$ emission reductions were due to container production (57.8 billion gallons and 45 thousand tons respectively). Container operations also accounted for a very large share of the N and P reductions under both the conservative and optimistic scenarios, accounting for at least 85% of the N and P reductions.

Table 6. Total magnitude of potential yearly environmental benefits of wireless sensor irrigation networks by region (assuming 100% adoption). Reductions in nitrogen (N) and phosphorus (P) emissions are based on conservative and optimistic scenarios (Table 3 and 4 respectively).

Region	Operation type	Reduction in water use (million gal.)[y]	Reduction in carbon dioxide emissions (ton)[x]	Conservative scenario		Optimistic scenario	
				Reduction in N runoff (lb)[w]	Reduction in P runoff (lb)[w]	Reduction in N runoff (lb)[w]	Reduction in P runoff (lb)[w]
All regions	Greenhouse	12,884.4	8,859.3	96,491.8	126,600.3	141,153.0	184,176.2
	Container	57,823.5	45,104.4	1,134,991.3	674,865.1	2,496,981.3	1,484,701.3
	Field	46,872.9	25,914.2	13,794.3	---	22,070.5	---
	Total	**117,580.8**	**79,8789.0**	**1,245,277.4**	**801,465.4**	**2,660,204.7**	**1,668,877.5**

[y]1 gal.= 3.785412 L, [x]1 ton = 0.9071847 Mg, [w]1 lb = 0.4535924 Kg

Reduction per million dollars of output

It is also helpful to look at benefits as reductions per amount of output ($) to put numbers in perspective. To do this, the total sales for the region were divided by the reduction amount that we estimated, to understand reductions per million dollars output (Table 7). Ratios are similar in table 6 and 7, but the magnitudes are different. The complete table is at the end of this module.

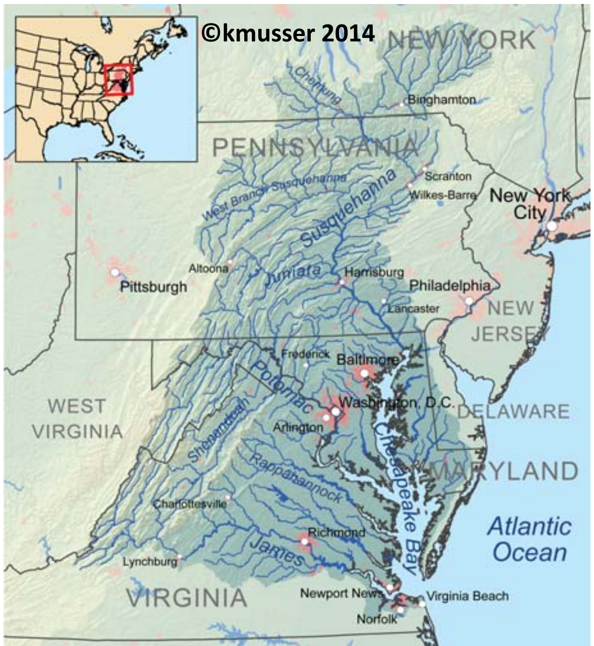
Table 7. Potential environmental benefits of wireless sensor irrigation networks by region per million dollars of output per year. U.S. Total reflects total nationwide environmental benefits divided by national sales. Reductions in nitrogen (N) and phosphorus (P) emissions are based on conservative and optimistic scenarios (Table 3 and 4 respectively).

Region	Operation type	Total sales (million $)[z]	Reduction in water use (millions gal.)[y]	Reduction in CO_2 emissions (ton)[x]	Conservative scenario		Optimistic scenario	
					Reduction in N runoff (lb)[w]	Reduction in P runoff (lb)[w]	Reduction in N runoff (lb)[w]	Reduction in P runoff (lb)[w]
All regions	Greenhouse	$2,219.05	2.9	3.99	43.48	57.06	63.60	83.00
	Container	$6,411.37	4.5	7.03	177.03	105.27	389.47	231.57
	Field	$3,357.47	7.0	7.72	4.10	---	6.57	---
	Total	**$11,987.89**	**4.9**	**6.66**	**103.88**	**66.87**	**221.92**	**139.22**

[z] Total sales are derived from U. S. Department of Agriculture (2010b).

[y]1 gal.= 3.785412 L, [x]1 ton = 0.9071847 Mg, [w]1 lb = 0.4535924 Kg

Chesapeake Bay: A case study



The Chesapeake Bay Watershed includes 6 states and Washington D.C. and is currently under federally mandated total maximum daily load (TMDL) limits for nitrogen, phosphorus and sediment.

The Chesapeake Bay, in the Mid-Atlantic region of the United States, represents a meaningful test site for determining the impact of sensor network adoption. Currently, total maximum daily load (TMDL) limits are being implemented in the six states and Washington D.C., that make up this watershed. There are increasing regulations and fines associated with failing to implement nutrient reductions as part of the TMDL process. Although sensor networks cannot account for all of the necessary pollution reductions by themselves, they can be a tool that is used to meet the mandates set out in the TMDL policy. Although non-point pollution (farms, houses etc.) are not currently regulated as part of TMDL implementation, they can still be used as a tool to help reduce pollution loads. There is also a possibility that in time, regulations may be passed limiting non-point pollution such as sediment, nitrogen, and phosphorus coming from agriculture.

Since public benefits are dependent on the adoption rate of sensor networks, the impact of three different adoption rates for the Chesapeake Bay are shown in Table 8. Under then 100% adoption scenario, there is the potential for regional reductions of over 10,000 acre feet of water, almost 2,500 tons of CO_2, over 70 tons of N, and over 42 tons of P per year. All this can be accomplished with a technology that can also increase profitability.

Table 8. Reductions in resource use and emissions in the Chesapeake Bay Watershed associated with the use of WSIN technology for ornamental production, assuming various adoption rates. Reductions in water use and carbon dioxide (CO_2) emissions are based on a 50% reduction in the application of irrigation water. Reductions in nutrient emissions are based on the optimistic scenario (see Table 4).

Chesapeake watershed Reductions in:	**25% adoption rate**	**50% adoption rate**	**100% adoption rate**
Water use (million gal.)^x	858	1715	3431
Carbon emissions (ton)^y	617	1,234	2,468
Nitrogen discharge (lb)^z	35,475	70,947	141,894
Phosphorus discharge (lb)^z	21,017	42,035	84,069
^{x}1 gal.= 3.785412 L, ^{y}1 ton = 0.9071847 Mg, ^{z}1 lb = 0.4535924 Kg			

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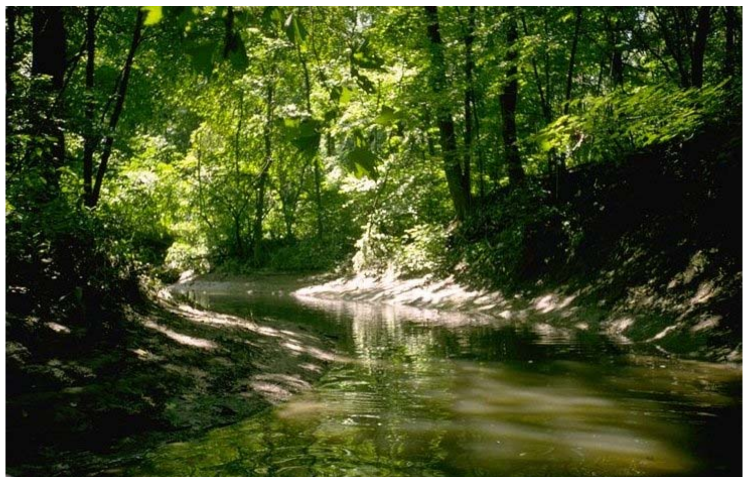
Based on the assumptions that were made, increasing adoption rates of sensor technology for ornamental production leads to reductions in water, carbon emissions, and N and P runoff, all of which will help meet TMDL requirements. It is likely that TMDL regulations will be implemented in other distressed watersheds, and sensor networks may be a way to reduce nutrient, sediment and water runoff to lower the impact of plant production on the environment.

Conclusions

Based on the simulations that we performed as part of this project, sensor network adoption by greenhouse, container, and field ornamental growers provides a number of public benefits. Sensor networks have been shown to reduce the volume of water used, which also impacts the carbon dioxide emissions associated with pumping water. We have also calculated reductions in nitrogen and phosphorus runoff, which would yield major benefits for surface and groundwater reserves and the aquatic life that inhabits them.

As we have discussed, it is too early to directly measure public benefits of sensor networks, because this technology is just beginning to be adopted by commercial growers. As this technology spreads however, public benefits will be able to be measured directly. It will be interesting to see how actual benefits track with our estimates given the advances that we have seen with this technology over the 5 year lifespan of this project.

Based on the assumptions described here, it is reasonable to expect that sensor networks have the potential for major public benefits through reductions in water, CO_2, nitrogen and phosphorus. The relatively high up-front costs of sensor networks may hinder some potential adopters from purchasing systems, which decreases the overall public benefit. Cost share or other financial incentives would be ways to reduce the initial cost of these systems, and increase the public benefits associated with them.



Wireless sensor networks can have a role to play in restoring water quality through reductions in agricultural sediment and nutrient runoff.

Additionally, extending the use of these sensor networks into other areas of plant production, including fruit and vegetable production, is a promising possibility as their use becomes more widespread. We are excited to see this technology become widely used in agriculture.

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Table 1. Annual potential regional reduction in water use through the adoption of wireless sensor irrigation networks (WSIN) for ornamental production. Water reductions are reported using a 50% and 100% adoption scenario, and assuming a 50% reduction in water use once WSIN are adopted at an operation.

		Annual reduction in water use (million gallons)[z]	
Region	**Operation type**	**50% adoption**	**100% adoption**
Appalachian	Greenhouse	328.5	657.0
	Container	1,681.3	3,362.6
	Field	1,000.9	2,001.8
Midwest	Greenhouse	620.2	1,240.3
	Container	1,556.8	3,113.6
	Field	926.8	1,853.6
Mountain/South-central/Great Plains	Greenhouse	1,007.4	2,014.8
	Container	4,790.3	9,580.6
	Field	8,046.5	16,092.9
Northeast	Greenhouse	435.9	871.8
	Container	949.6	18,99.23
	Field	1,595.2	3,190.3
Pacific	Greenhouse	1,424.0	2,848.0
	Container	13,335.6	26,671.1
	Field	7,939.0	15,878.1
Southeast	Greenhouse	2,626.2	5,252.4
	Container	6,598.3	13,196.5
	Field	3,928.1	7,856.2
All regions	Greenhouse	6,442.2	12,884.4
	Container	28,911.8	57,823.6
	Field	23,436.5	46,872.9
	Total	58,790.4	117,580.9

[z]1 gal.= 3.785412 L

Table 2. Annual potential regional reduction in Carbon Dioxide (CO_2) emissions (Mg) by using wireless sensor irrigation networks. Annual CO_2 reductions are based on a 50% reduction in pumping volumes, for 50% and 100% of ornamental operations.

Region	Operation type	Annual reduction in CO_2 emissions (tons)[z]	
		50% adoption	100% adoption
Appalachian	Greenhouse	229	457
	Container	1,171	2,341
	Field	697	1,394
Midwest	Greenhouse	343	687
	Container	861	1,723
	Field	44	88
Mountain/South-central/Great Plains	Greenhouse	617	1,233
	Container	4,926	9,852
	Field	2,933	5,865
Northeast	Greenhouse	352	704
	Container	1,289	2,577
	Field	767	1,534
Pacific	Greenhouse	1,028	2,057
	Container	9,632	19,263
	Field	5,734	11,468
Southeast	Greenhouse	1,861	3,720
	Container	4,674	9,348
	Field	2,782	5,564
All regions	Greenhouse	4,429	8,859
	Container	22,552	45,104
	Field	12,958	25,914
	Total	39,939	79,879

[z]1 ton = 0.9071847 Mg

Table 5. Potential reductions in annual nitrogen (N) and phosphorus (P) runoff for ornamental production with adoption of wireless sensor irrigation networks. Two adoption rates (50% and 100%), and 2 emissions reduction rates conservative (Table 3), and optimistic (Table 4) were used. Note: P values are not reported for field operations because reliable data for P runoff could not be obtained outside of Maryland.

		Conservative scenario				Optimistic scenario			
		50% adoption		100% adoption		50% adoption		100% adoption	
Region	**Operation type**	**Pounds of N reduced[z]**	**Pounds of P reduced[z]**	**Pounds of N reduced[z]**	**Pounds of P reduced[z]**	**Pounds of N reduced[z]**	**Pounds of P reduced[z]**	**Pounds of N reduced[z]**	**Pounds of P reduced[z]**
Appalachian	Greenhouse	1,689	2,039	3,380	4,079	2,471	2,471	4,943	4,943
	Container	40,256	24,760	80,513	49,520	88,564	54,474	177,128	108,946
	Field	728	---	1,453	---	1,164	---	2,326	---
Midwest	Greenhouse	3,591	4,960	7,183	9,921	5,254	7,258	10,505	14,513
	Container	66,229	39,571	132,458	79,139	145,703	87,054	291,407	174,108
	Field	1,338	---	2,676	---	2,143	---	4,284	---
Mountain/ South-central Great Plains	Greenhouse	5,794	704,1.6	11,587	14,083	8,477	10,302	16,951	20,602
	Container	140,514	87,731	281,025	175,461	309,127	193,008	618,255	386,014
	Field	1,616	---	3,234	---	2,586	---	5,174	---
Northeast	Greenhouse	2,247	3,120	4,491	6,239	3,285	4,564	6,570	9,125
	Container	94,966	55,649	189,932	111,296	208,925	122,427	417,850	244,852
	Field	174	---	348	---	278	---	556	---
Pacific	Greenhouse	17,663	24,868	35,329	49,736	25,840	36,378	51,681	72,757
	Container	72,073	46,932	144,147	93,864	158,563	103,251	317,124	206,502
	Field	1,594	---	3,186	---	2,549	---	5,099	---
Southeast	Greenhouse	17,260	21,270	34,522	42,543	25,249	31,116	50,501	62,232
	Container	153,459	82,790	306,916	165,582	337,609	182,141	675,216	364,280
	Field	1,448	---	2,895	---	2,317	---	4,632	---
All regions	Greenhouse	48,246	63,301	96,492	126,600	70,577	92,087	141,153	184,176
	Container	567,496	337,432	1,134,991	674,865	1,248,492	742,351	2,496,981	1,484,701
	Field	6,896	---	13,794	---	11,034	---	22,070	---
	Total	622,638	400,732	1,245,277	801,465	1,330,102	834,438	2,660,205	1,668,877

[z]1 lb = 0.4535924 Kg

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Table 6. Total magnitude of potential yearly environmental benefits of wireless sensor irrigation networks by region (assuming 100% adoption). Reductions in nitrogen (N) and phosphorus (P) emissions are based on a conservative scenario (Table 3), or an optimistic scenario (Table 4).

Region	Operation type	Total sales (million $)[z]	Reduction in water use (million gal.)[y]	Reduction in carbon dioxide emissions (ton)[x]	Conservative scenario		Optimistic scenario	
					Reduction in N runoff (lb)[w]	Reduction in P runoff (lb)[w]	Reduction in N runoff (lb)[w]	Reduction in P runoff (lb)[w]
Appalachian	Greenhouse	$123.5	657.1	457.46	3,380	4,079	4,943	4,943
	Container	$423.4	3,362.6	2,341.31	80,513	49,520	177,128	108,946
	Field	$497.7	2,001.8	1,394.42	1,453	---	2,326	---
Midwest	Greenhouse	$172.8	1,240.4	686.74	7,183	9,921	10,505	14,513
	Container	$1,230.0	3,113.6	1,722.91	132,458	79,139	291,407	174,108
	Field	$526.5	1,853.6	88.18	2,676	---	4,284	---
Mountain/ South-central/ Great Plains	Greenhouse	$261.5	2,014.8	1,233.49	11,587	14,083	16,951	20,602
	Container	$1,230.0	9,580.6	9,852.46	281,025	175,461	618,255	386,014
	Field	$526.5	16,092.9	5,865.40	3,234	---	5,174	---
Northeast	Greenhouse	$103.70	871.8	704.38	4,491	6,239	6,570	9,125
	Container	$1,367.8	1,899.3	2,577.20	189,932	111,296	417,850	244,852
	Field	$149.4	3,190.3	1,534.42	348	---	556	---
Pacific	Greenhouse	$1,096.4	2,848.0	2,056.91	35,329	49,736	51,681	72,757
	Container	$1,263.7	26,671.1	19,262.88	144,1467	93,864	317,124	206,502
	Field	$1,113.6	15,878.0	11,468.44	3,186	---	5,099	---
Southeast	Greenhouse	$461.2	5,252.4	3,720.30	34,522	42,543	50,501	62,232
	Container	$896.5	13,196.5	9,347.60	306,916	165,582	675,216	364,280
	Field	$543.9	7,856.2	5,564.47	2,895	---	4,632	---
All regions	Greenhouse	$2,219.0	12,884.4	8,859.27	96,492	126,600	141,153	184,176
	Container	$6,411.4	57,823.5	45,104.36	1,134,991	674,865	2,496,981	1,484,701
	Field	$3,357.5	46,872.9	25,914.23	13,794	---	22,070	---
	Total	**$11,987.9**	**117,580.8**	79,878.97	1,245,277	801,465	2,660,205	1,668,878

[z] Total sales are derived from U. S. Department of Agriculture (2010b).

[y]1 gal.= 3.785412 L, [x]1 ton = 0.9071847 Mg, [w]1 lb = 0.4535924 Kg

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Table 7. Potential environmental benefits of wireless sensor irrigation networks by region per million dollars of output per year. U.S. Total reflects total nationwide environmental benefits divided by national sales. Reductions in nitrogen (N) and phosphorus (P) emissions are based on a conservative scenario (Table 3), or an optimistic scenario (Table 4).

Region	Operation type	Total sales (million $)	Reduction in water use (millions gal.)[y]	Reduction in CO_2 emissions (ton)[x]	Conservative scenario		Optimistic scenario	
					Reduction in N runoff (lb)[w]	Reduction in P runoff (lb)[w]	Reduction in N runoff (lb)[w]	Reduction in P runoff (lb)[w]
Appalachian	Greenhouse	$123.5	5.3	3.70	27.4	33.0	40.0	40.0
	Container	$423.4	7.9	5.53	190.2	307.1	418.3	257.3
	Field	$497.7	4.0	2.80	2.9	---	4.7	---
Midwest	Greenhouse	$172.8	7.2	3.97	41.6	57.4	60.8	84.0
	Container	$1,230.0	2.5	1.40	107.7	64.4	236.9	141.6
	Field	$526.5	3.5	0.17	5.1	---	8.1	---
Mountain/ South-central/ Great Plains	Greenhouse	$261.5	7.7	4.72	44.3	53.9	64.8	78.8
	Container	$1,230.0	7.8	8.01	228.5	142.7	502.7	313.9
	Field	$526.5	30.6	11.14	6.2	---	9.8	---
Northeast	Greenhouse	$103.70	8.4	6.79	43.3	60.2	63.4	88.0
	Container	$1,367.8	1.4	1.88	138.9	81.4	305.5	179.0
	Field	$149.4	21.4	10.27	2.3	---	3.7	---
Pacific	Greenhouse	$1,096.4	2.6	1.87	32.2	45.4	47.1	66.4
	Container	$1,263.7	21.1	15.24	114.1	74.3	251.0	163.4
	Field	$1,113.6	14.3	10.30	2.9	---	4.6	---
Southeast	Greenhouse	$461.2	11.4	8.07	74.9	92.2	109.5	134.9
	Container	$896.5	14.7	10.43	342.3	184.7	753.1	406.3
	Field	$543.9	14.4	10.23	5.3	---	8.5	---
All regions	Greenhouse	$2,219.0	2.9	3.99	43.5	57.1	63.6	83.0
	Container	$6,411.4	4.5	7.03	177.0	105.3	389.5	231.6
	Field	$3,357.5	7.0	7.72	4.1	---	6.57	---
	Total	**$11,987.9**	**4.9**	6.66	103.9	66.9	221.9	139.2

[y]1 gal.= 3.785412 L, [x]1 ton = 0.9071847 Mg, [w]1 lb = 0.4535924 Kg

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